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Impact of climate change on life cycle greenhouse gas (GHG) emissions of biofuels

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Doctor of Philosophy

RESEARCH DECLARATION

I declare that this report is entirely my own work and that any use of the work of others has been appropriately acknowledged as in-text citations and compiled in the reference list. I also confirm that the project has been conducted in compliance with the University's research ethics policy.

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DEDICATION

To my family

ABSTRACT

Reducing anthropogenic GHG emissions globally is a key driver for the development of renewable energy sources. A key route towards achieving this is to replace fossil-based fuels with renewable and low carbon energy technologies such as biofuels from energy crops. Cereals and oil-seed crops such as corn, wheat, and soybean are the main feedstocks primarily used for biofuels production and the key characteristics of these crops are high biomass and energy yield per ha. However, there are concerns about the availability and sustainability of these crops for biofuels production in the face of a changing climate since crop productivity is inherently sensitive to climate. Therefore, an understanding of the impacts of climate change on energy crops production as feedstocks for biofuels production and their potential for life cycle GHG emissions reductions is crucial for making decisions on future biofuels production.

This thesis examined potential climate change impacts on the productivity of two major biofuel crops: corn (*Zea mays* L.) and soybean (*Glycine max*) in Gainesville, USA and one major biofuel crop: wheat (*Triticum spp*.) in Rothamsted, UK. The overall objective was to calculate the potential impacts of combined changes in climate variables: surface air temperature (*T*), precipitation (*P*), and atmospheric concentration of CO_2 ($[CO_2]$) on life cycle GHG emissions savings of biofuels from corn, soybean, and wheat.

The methodology was underpinned by life cycle thinking. Life cycle assessment (LCA) models linked to cropping system models (CSM) were used in the analysis. In assessing the impact of climate change on corn, wheat, and soybean crops yields, two applications of the CERES (Crop-Environment Resource Synthesis) model: CERES-Wheat (for wheat) and CERES-Maize (for corn), and CROPGRO (Crop Growth) model application: CROPGRO-

Soybean of the Decision Support System for Agrotechnology Transfer (DSSAT-CSM) v4.0.2.0 model were used using observed weather data from the baseline (1981-1990) period for each study site. These models describe, based on daily data, the basic biophysical processes taking place at the soil-plant-atmosphere interface as a response to the variability of different processes such as: photosynthesis, specific phenological phases, evapotranspiration, and water dynamics in soil. Compared with the baseline, *T* was projected to increase by +1.5, +2, +2.5, +3, +3.5, +4, +4.5, and +5 ^oC, *P* was projected to change by ±5, ±10, ±15, and ±20%, and *[CO_2]* was projected to increase by +70, +140, +210, +280, and + 350 ppm for Gainesville, USA. For Rothamsted, UK, *T* was projected to increase by +0.5, +1.5, +2.5, +3.5, and +4.5 ^oC, *P* was projected to change by ±10, and ±20%, and *[CO_2]* was projected to increase by +70, +210, and + 350 ppm.

Simulated yields output (grain/seeds and biomass) from the CSM models were used as inputs into the LCA models. Potential life cycle GHG emissions savings were calculated for corn-based biofuels: corn bioethanol (CBE), corn integrated biomethanol (CIBM), and corn integrated bioelectricity (CIBE); soybean-based biofuels: soybean biodiesel (SBD), soybean integrated biomethanol (SIBM), and soybean integrated bioelectricity (SIBE); wheat-based biofuels: wheat bioethanol (WBE), wheat integrated biomethanol (WIBM), and wheat integrated bioelectricity (WIBE).

Results indicated that under the baseline (1981-1990) scenario, production and use of CBE, CIBM, CIBE, SBD, SIBM, SIBE, WBE, WIBM, and WIBE could save -4743.32 kg CO_2-equiv. ha^{-1}, -8573.31 kg CO_2-equiv. ha^{-1}, and -10996.7 kg CO_2-equiv. ha^{-1}, -2655.41 kg CO_2-equiv. ha^{-1}, -3441.1 kg CO_2-equiv. ha^{-1}, and -1350.04 kg CO_2-equiv ha^{-1}, -2776.1 kg CO_2-equiv. ha^{-1}, -500.87 kg CO_2-equiv. ha^{-1} and -4648.93 kg CO_2-equiv. ha^{-1} respectively, of the total life cycle GHG emissions of CO_2, CH_4, and N_2O for the production and utilization of an energetically equivalent amount of fossil-based fuel counterpart, which they displaced.

However, model predictions of future life cycle GHG emissions savings for both crops showed that the responses of corn, soybean, and wheat to simultaneous changes in *T*, *P*, and *[CO_2]* were different under different climate change scenarios. In the future period life cycle GHG emissions savings of corn-based biofuels was predicted to decline in all cases ranging from -4.2% to -46.1%, -2.6% to -37.7%, and -1.6% to -33.4% for CBE, CIBM, and CIBE, respectively compared with the baseline (1981-1990) period. In contrast, model predictions showed that life cycle GHG emissions savings of wheat-based biofuels would increase under all climate change scenarios ranging from +2.5% to +33.5%, +0.1% to +37.8%, and +1.0% to +34.4% for WBE, WIBM, and WIBE, respectively. On the other hand, the life cycle GHG emissions savings of soybean-based biofuels was predicted to increase by +0.22% to +27%, +0.1% to 28%, and +0.1% to +31.6% for SBD, SIBM, and SIBE, respectively under some climate change scenarios (e.g., *[CO_2]* = 680; *P* = +20%; and *T* = +1.5 ^{o}C scenario) and also decline by -0.7% to -60.8%, -0.1% to -44.6%, and -0.1% to -82.6% for SBD, SIBM, and SIBE, respectively under some climate change scenarios (e.g., *[CO_2]* = 400; *P* = -20%; and *T* = +5 ^{o}C scenario).

These results revealed that the potential impacts of climate change on energy crops productivity and net life cycle GHG emissions savings could be very large and diverse, and that the anticipated life cycle GHG emissions reductions of biofuels would not be the same in the future.

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ACRONYMS, SYMBOLS, CONVERSION FACTORS, AND ENERGY EQUIVALENTS

ALMANAC	Agricultural Land Management Alternative with Numerical Assessment Criteria
AGW	Anthropogenic Global Warming
AR4	Fourth Assessment Report of the IPCC
AR5	Fifth Assessment Report of the IPCC
BD-R	Rapeseed derived biodiesel
BD-S	Soybean derived biodiesel
BIGCC	Biomass Integrated Gasification and Combined Cycle
BtL	Biomass to Liquid
C	Carbon
CBE	Corn Bioethanol
CCA	Climate Change Act
CD	Conventional Diesel
CERES-Maize	Crop Environment Resource Synthesis- Maize
CERES-Wheat	Crop Environment Resource Synthesis-Wheat
CG	Conventional Gasoline
CH_4	Methane
CIBE	Corn Integrated Bioelectricity
CIBM	Corn Integrated Biomethanol
CML	Centre of Environmental Science of Leiden University
CNG	Compressed Natural Gas
CO	Carbon monoxide
COCO	CAPE-OPEN to CAPE-OPEN
CO_2	Carbon dioxide
CO_2-equiv.	Carbon dioxide equivalent
CROPGRO-Soybean	Crop Growth-Soybean
CropSyst	Cropping Systems Simulation model

CSM	Cropping System Model
CtL	Coal to Liquid
CV	Calorific Value
d.b	dry basis
DDGS	Dried Distillers Grain with Solubles
DECC	Department of Energy and Climate Change
dLUC	Direct Land Use Change
DSSAT	Decision Support System for Agrotechnology Transfer
EC	European Commission
E-C	Cassava derived ethanol
E-Co	Corn derived ethanol
EEA	European Environmental Agency
EJ	Exajoules
EMIC	Earth System Model of Intermediate Complexity
ENSO	El Nino Southern Oscillation
EPIC	Environmental Policy Integrated Model
E-S	Soybean derived ethanol
EU	European Union
FACE	Free Air Carbon dioxide Enrichment Experiment
F-gases	Fluorinated gases
FT	Fischer Tropsch
g	gram
GCM	General Circulation Models
GDD	Growing Degree Days
GHG	Greenhouse Gas
GLAM	General Large Area Model
GLYCIM	Soybean Simulation Model
Gt	Gigatons
GtL	Gas to Liquid

GW	Global Warming
GWP	Global warming Potential
GWP100	100-year Global Warming Potential
H	Hydrogen
ha	hectare
H_2O	Water
HFCs	Hydrofluorocarbons
HHV	Higher Heating Value
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICASA	International Consortium for Application of Systems Approaches
iLUC	Indirect Land Use Change
IPAR	Incident Photosynthetically Active Radiation
IPCC	Intergovernmental Panel on Climate Change
J	Joules
K	Potassium
kWh	kilowatt-hour
kg	kilogram
km	kilometer
LAI	Leaf Area Index
LCA	Life Cycle Assessment
LCI	Life cycle Inventory
LCIA	Life cycle Impact Assessment
LHV	Lower Heating Value
Mha	Million hectares
MJ	Megajoules
MT	Metric tonnes
MWh	Megawatt-hour
N	Nitrogen

NASS	National Agricultural Statistical Service
NCAR	National Centre for Atmospheric Research
NEV	Net Energy Value
NRCS	Natural Resources Conservation Service
N_2O	Nitrous oxide
O	Oxygen
P	Phosphorus
PAR	Photosynthetically Active Radiation
PEM	Palm oil Methyl Ester
PEP	Phosphoenol Pyruvate
PFCs	Perfluorocarbons
PGR	Plant Growth Regulator
ppm	Parts per million
RES	Renewable Energy Sources
RFS	Renewable Fuel Standard
RUBISCO	Ribulosediphosphate Carboxylase
RUE	Radiation Use Efficiency
S	Sulphur
SALO	Sandy Loam
SBD	Soybean Biodiesel
SCL	Sandy Clay Loam
SCM	Simple Circulation Models
SF_6	Sulphur hexafluoride
SIBE	Soybean Integrated Bioelectricity
SIBM	Soybean Integrated Biomethanol
SOC	Soil Organic Carbon
SR	Substitution Ratio
SRC	Short Rotation Coppice
SRES	Special Report on Emissions Scenarios

SRF	Surface air temperature
SWAP	Soil Water Atmosphere Plant Model
SWAT	Soil and Water Assessment Tool
TJ	Terajoules
tkm	ton kilometer
T	Tones
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USDA	United States Department of Agriculture
WBE	Wheat Bioethanol
WIBE	Wheat Integrated Bioelectricity
WIBM	Wheat Integrated Biomethanol
Wh	watt-hour
wt	weight
yr	year

1 British thermal unit [Btu] = 1055 J = 252 cal

1 Btu = 1 Btu = 0.000292875 kilowatt-hour

1 calorie (cal) = 4.1868 J

$[CO_2]$ = CO_2 concentration

1 cubic metre = 35.315 cubic feet = 6.2898 barrels

1 cubic meter (m^3) = 1000 litre (l)

1 ha = 10 000 square meter (m^2)

1 ha = 2.47105 acres

1 joule (J) = 0.2388 cal

1 kg = 2.20462 pounds (lb)

1,000 kWh = 3.41 million BTU

1 kilowatt-hour (kWh) = 3.6 x 10^6 J = 3.6 million Joules = approx. 860 kcal

1 litre = 0.02838 bushel (bu)

1 therm = 100,000 BTU = 105.5 MJ = 29.3 kWh

1 tonne of coal equivalent (TCE) = 29.3 GJ (net calorific value) = 7 000 Mcal

1 tonne of oil equivalent (TOE) = 42 GJ (net calorific value) = 10 034 Mcal

1 tonne of crude oil = approx. 7.3 barrels

1 tonne of natural gas liquids = 45 GJ (net calorific value)

1 tonne of fuel wood = 0.3215 TOE

1 TOE = 7.3 barrel crude oil

1 UK gallon = 4.546 litres

1 000 standard cubic metres of natural gas = 36 GJ (net calorific value)

1 US gallon =3.785 litres

bu x 0.025400 = MT corn

bu x 0.027216 = MT wheat or soybeans

bu/acre x 0.06725 = MT/ha wheat or soybeans

bu/acre x 0.06277 = MT/ha corn

Billions of Btu = 1.0E+09 Btu

'CH' = Switzerland specific LCI data

Coal = 25 million BTU/ton

Crude Oil = 5.6 million BTU/barrel

Exa = 10^{18}

Gasoline = 5.6 million BTU/barrel (a barrel is 42 gallons) = 1.33 therms / gallon

Giga = 10^9

kilo = 10^3

m^3 = cubic meter

m^2 = square meter

Mega = 10^6

Millions of Btu = 1.0E+06 Btu

Natural gas = 1030 BTU/cubic foot

Natural gas liquids = 4.2 million BTU/barrel

Oil = 5.78 million BTU/barrel = 1700 kWh / barrel

P = Precipitation

Quad = 1.0E+15 Btu

'RER' = Europe specific LCI data

T =Temperature

Tera = 10^{12}

Therm = 1.0E+05 Btu

'US' – USA specific LCI data

CHAPTER 1: GENERAL INTRODUCTION TO THE RESEARCH

1.1 Introduction

During the first commitment period of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) [1], which started in 2008 and ended in 2012, 37 industrialized countries, including China, Japan, and the European Union (EU) committed to reduce their greenhouse gas (GHG) emissions to an average of five percent against 1990 baseline levels. Furthermore, during the second commitment period, countries such as the EU have committed to reduce their GHG emissions by at least 18 percent below 1990 levels in the eight-year period from 2013 to 2020 [1]. For instance, in an attempt to comply with the 20/20/20 targets set by the EU, the UK is legally bound by the 2008 Climate Change Act (CCA), to achieve a mandatory 80% cut in the UK's carbon emissions by 2050 and a benchmark 35% reduction by 2020, below 1990 baseline levels [2]. A key route towards achieving these targets is to replace fossil based fuels with renewable and low carbon energy technologies [3, 4]. Renewable energy from biomass has been acknowledged as a significant contributor to these [5-12]. Biomass as a renewable energy source contributes towards reducing greenhouse gas emissions, diversification of fuel supplies, and the development of long-term replacements for fossil fuels [13-15]. Cereals and oil-seed crops such as corn, wheat, and soybean are the main feedstock primarily used for biofuels production and the key characteristics of these crops are high biomass and energy yield per ha [16]. However there are concerns about the availability and sustainability of these crops for the biofuels production [17-22] in the face of a changing climate since crop productivity is inherently sensitive to a number of climatic factors, including temperature, precipitation, and atmospheric concentration of CO_2 [23-28].

Undoubtedly, climate change would have both benefits and drawbacks on the productivity of energy crops [29-32]. Increasing atmospheric GHG concentrations of CO_2, CH_4 and other gases in the atmosphere as a result of human activities are expected to induce significant warming over the next century and beyond [33]. According to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) [34], climate change is expected to continue throughout the 21st century. Thus, since energy crop productivity is affected by climate change, the potential GHG reductions and net energy value (NEV) from energy crops would be at risk.

Previous studies on the impact of climate change on crop production are mainly focused on food production [35-39] and bioenergy feedstock supply [40], while studies on climate change impacts on the yield of bioenergy crops mostly, only focused on feedstock supply without paying attention to the potential impact on biofuel production at the same time. Few studies linked biofuel production, energy crop and climate change together [16, 41]. Therefore, understanding the impacts of climate change on energy crops production such as corn, wheat, and soybean as feedstock for biofuels production and their potential for GHG emissions reductions is crucial for making decisions on future biofuels production.

1.2 Energy and sustainability

Sustainable development is now firmly on the agenda of all large and progressive companies. Sustainable development can be broadly defined as living, producing and consuming in a manner that meets the needs of the present without negatively affecting the ability of future generations to meet their own needs [42]. Sustainability is a key principle in natural resource management, and it involves operational efficiency, minimisation of environmental impact and socio-economic considerations [43]. Environmental sustainability aspects are among the important issues in the current discussion about bioenergy production systems, since ‘renewable’ does not mean ‘sustainable’. Sustainability of global energy systems is therefore, an important prerequisite for sustainable development.

Energy demand to meet social and economic development and improve human welfare is increasing rapidly. Energy plays a key role in the growth and economic development of any nation. All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility and communication) and to serve productive processes.

Historically, the Earth has been experiencing an accelerated population growth, climate change, and soaring oil prices. Currently, there are nearly 7 billion people inhabiting the planet, and it is projected to reach 9.3 billion in 2050 and more than double to 15 billion by the end of the 21st century [44, 45]. Energy demand is likely to continue to grow throughout the century. Substantial increase in the production of energy is therefore required to meet the growing demand for energy (Figure 1.1).

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Figure 1.1: World total energy consumption 2005 to 2035 (1 BTU=1055J) [46].

Meanwhile, over 80% of today's energy is generated by conventional fossil fuels such as coal, crude oil, and natural gas (Figure 1.2) [46, 47]. However, global use of these conventional fossil fuels, which has increased to dominate energy supply, led to a rapid increase in atmospheric carbon dioxide (CO_2) concentration, which raises a number of global concerns.

Increased rate of depletion of fossil fuels [48] and the environmental impacts generated by the use of conventional fossil fuels [49] are some of the major concerns arising from the use of conventional fossil energy systems. The combustion of fossil fuels is by far the largest contributor to the increasing atmospheric concentration of GHG [50, 51]. GHG emissions resulting from the provision of energy services have contributed significantly to the historic increase in global atmospheric GHG concentrations. For instance, according to [52] the

European Environmental Agency (EEA) reported that the energy industry was responsible for almost 80% of the total GHG in the EU in 2009.

Figure 1.2: Shares of energy sources in total global primary energy supply in 2008 [53].

Anthropogenic GHG emissions associated with the combustion of these conventional fossil fuels at or above current rates will cause further global warming and induce climate changes [50]. According to the IPCC [50] most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. In early 2013, atmospheric CO_2 concentrations had increased to over 400 ppm, or 39% above preindustrial levels and is further projected to grow in the future above 660 ppm from the remaining fossil fuel deposits (see Figure 1.3) [53].

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Figure 1.3: Potential emissions from remaining fossil fuel resources deposit [53].

Currently, there are a number of options such as renewable energy sources for lowering GHG emissions from the energy system while still satisfying the global demand for energy services**.** In recent years, ambitious targets and climate policy measures have been formulated by many nations (e.g. EU, USA and Brazil) for the development and use of sustainable energy supplies typically driven by three major concerns: climate change, security of energy supply and rural development. One of the key components towards achieving these policy goals is securing the energy future through cleaner renewable energy sources that can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs. These include bioenergy, solar energy, wind energy, hydropower energy and geothermal energy.

1.3 Biomass as a renewable energy source

Biomass (e.g. wood) was the first fuel used by humanity. However, the rise in the use of fossil since the revolution has resulted in the decline in the use of biomass as a primary energy source in the developed world. For instance, at the beginning of the 21st Century only 3% of energy use in USA comes from biomass. In developing countries like the Sub-Saharan Africa fuel wood is the most important fuel resources and contribute over 90% of the fuel available for heating and cooking in these regions.

Bioenergy from renewable biomass plays an important role in the daily livelihoods of billions of people all over the world and has large potential to mitigate climate change and at the same time if properly implemented may provide huge benefits and contribute to economic and social development. It offers the opportunity to contribute to secure energy supply as well as the reduction of negative environmental and health impacts [5-12]. Biomass can be defined as "*recent organic matter originally derived from plants as a result of the photosynthetic conversion process or from animals, and which is destined to be utilized as store of chemical energy to provide heat, electricity, or transport fuels*" [54]. It is a fuel in the same sense as fossil fuels (coal, oil, and natural gas) though fossil fuels have higher energy values per unit mass, and has the potential to be a major contributor to the delivery of the ambitious targets set by many nations (e.g. EU, USA, China, India and Brazil) for renewable energy generation when produced in a sustainable fashion [55].

Biomass resources (see Figure 1.4) can be classified into many different categories: fuelwood, agricultural and forest residues, organic wastes and, dedicated biomass production on different lands types (pasture, arable, and marginal lands). These can be directly used as feedstocks to produce electricity or heat, or can be used to create solid, liquid, gaseous fuels. They can also be used as feedstock for materials and chemicals. The range of bioenergy technologies is broad and the technical maturity varies substantially. The deployment of bioenergy technologies has increased dramatically over the last few decades in many parts of the globe such as the USA and Brazil, and their share is projected to grow substantially in the future [56].

Figure 1.4: Top: Shares of global primary biomass sources for energy Bottom: Fuel-wood used in developing countries [56].

Biomass is the largest and most important renewable energy option used all over the world providing about 50.2 EJ of bioenergy per year [15, 57]. In 2008, it was estimated that biomass accounted for 10.2% (out of the total 12.9% from renewable energy) of the total global primary energy supply (492 EJ) [58] (Figure 1.4). It will therefore play a crucial role in integrated systems of future energy supply and will be a valuable element in a new energy mix. Biomass currently contributes less than 10% and between 20-30% to the total energy share in developed and developing countries respectively [59-62]. However, in a number of countries (e.g. the Sub-Saharan Africa) biomass supplies 50-90% of the total energy demand [63]. There are projections that bioenergy from biomass could provide between 104.70-400 EJ/yr by 2050 [10, 20, 64-67]. Biomass has the potential to become the world's largest and most sustainable energy source and will be enough to meet the global energy demand in 2050 [12, 68].

Dedicated bioenergy crops are now being grown commercially all over the world. These are plants grown specifically for energy generation that are able to produce high yields of biomass in a short period of time when grown on marginal land (e.g. in the USA) and/or with minimal farming input of fertilizers and pesticides. A wide range of different bioenergy crops are being considered for biofuel applications including both established perennial C4 grasses that utilizes the C4 photosynthetic pathway such as *Miscanthus* and switchgrass (*Panicum virgatum*), as well as C3 short rotation coppice (SRC) that utilizes the C3 photosynthetic pathway such as willow and poplar. Dedicated bioenergy crops also include annuals, particularly corn (maize), wheat and soybeans, which currently make the largest contribution to bioenergy [22]. Other additional crops that can serve as bioenergy crops include sorghum, barley, sugarcane, oilseed, and palm oil.

1.3.1 Biomass potential for bioenergy

Biomass resources such as agricultural and forestry feedstock, as well as industrial and municipal solid wastes seem sufficient to support globally ambitious renewable energy targets/climate policy goals in an environmentally responsible way (see Figure 1.5). Its energy potential is thought to be the most promising among the renewable energy sources (RES), due to its availability worldwide. Apart from that, biomass has the unique advantage among the rest of the RES, to be able to provide solid, liquid and gaseous fuels that can be stored, transported and utilized, far away from the point of origin.

Figure 1.5: Environmentally compatible agricultural bioenergy potential [69].

Although bioenergy crops currently contribute a relatively small proportion to the total energy produced from biomass, the proportion is set to grow over the next few decades. It was claimed that tens of millions of hectares of ‘unused’ land were available in many countries of Africa, Asia and Latin America (Figure 1.6), and projected that up to one-fifth of the world’s agricultural land would be planted for bioenergy crops by 2050 [15]. Currently, only about 14 million ha (1 – 2% of the world’s arable land) is devoted to bioenergy crops production, but this is expected to increase to 4% by 2030 and 20% by 2050 [69].

1.3.2.Biofuels as a substitute for conventional fossil fuels

Biofuel, which provides about 10% of the total global energy supplies, is the most important renewable energy source used and could play a vital role in contributing towards reducing the dependence on finite fossil fuels, and reduce GHG emissions [11, 12, 70-74]. However, meeting such ambitious climate change targets and making bioenergy system competitive will require its production in a sustainable fashion – since “renewable” does not mean “sustainable” [18]. Biofuel from biomass has been hailed as a potential and reliable alternative to conventional fossil fuels that could deliver important benefits, contributing to GHG emission reductions, and enhance the security of energy supply [13, 75-79] (see Table 1.1).

Figure 1.6: Global land suitability for bioenergy plantations under rainfed cultivation and advanced management systems that assume availability of sufficient nutrients and mechanization. The upper map shows suitability for herbaceous and woody lignocellulosic plants - switchgrass, miscanthus, poplar, and willow. Lower map shows suitability for maize, soybean, cassava and sugarcane [58].

Table 1.1: List of selected liquid and gaseous biofuels, technologies, status and engine applications [80].

To comply with the global energy policy requirements, for example, in Europe, the EU Directive (*EU Directive 2009/28/EC*) on the promotion of the use of biofuels or other renewable fuels for transport within the EU which sets out the objective of 10% for biofuels in transport and also a minimum 35% reduction in GHG emissions to be achieved by biofuels during their life cycle by 2020 and 80% by 2050 below the 1990 baseline [81], dedicated agricultural bioenergy crops (e.g. switchgrass, willow, miscanthus, wheat, corn and soybean), agricultural and forest residues, and municipal solid wastes are being utilized as biofuel sources for both liquid fuels and electricity generation *via* either biological or thermochemical processes [7, 80, 82, 83]. Biofuels are potential low-carbon energy sources and, with the available conversion technologies, may substantially contribute to the renewable energy targets in the near future.

Biofuels are now widely considered as key components towards achieving sustainable energy supply on a global scale. Biofuel is a renewable energy source, which can be used as a substitute for conventional petroleum based fuels. The replacement of fossil fuels with biomass-based fuels has the potential to provide significant reductions in GHG emissions, and is regarded to be effective because the carbon released was part of the modern carbon cycle (Figure 1.7). In the case of fossil fuels, however, long-buried carbon is released that adds to the modern cycle. The term biofuel is referred to as solid (e.g. bio-char, charcoal), liquid (bioethanol, biodiesel, biomethanol), or gaseous (biogas, biosynthesis gas, and hydrogen) fuels that are predominantly produced from renewable biomass [12]. Some of the major benefits of using biofuels are listed in Table 1.2.

Table 1.2: Major benefits and drawbacks of biofuels [12].

Figure 1.7: Model of carbon cycle illustrating how energy carriers are derived from biomass. Biomass carbon is generated via photosynthesis upon fixing atmospheric CO_2 with a simultaneous conversion of solar energy into chemical energy stored in biomass [61].

1.3.3 Biofuels Classification

Biofuels can be classified into primary and secondary biofuels. Primary biofuels is referred to those biofuels that are used in an unprocessed form predominantly for heating, cooking, and electricity generation purposes (e.g. fuel wood, wood chips and pellets). Secondary biofuels are those produced through lignocellulosic biomass processing such as bioethanol, biodiesel, biogas, and biosyngas. Secondary biofuels can be further classified into first, second, and third-generation biofuels depending on the kind of raw material (biomass) feedstock used and the technology employed for their production [84-89]. First-generation biofuel feedstocks are primarily grains/seeds and vegetable oil. Second-generation feedstocks are predominantly lignocellulosic (non-food) materials such as agricultural residues. Third generation feedstocks are microalgal biomass.

Figure 1.8: Main conversion option for biomass energy carriers [58].

First-generation bioethanol and biodiesel primarily produced from cereals grain and edible vegetable oil respectively are currently the most common form of biofuel. Biodiesel is made through a transesterification process to produce methyl ester. A number of methods for the conversion of biomass to useful biofuels have now been developed; some of these are presented in Figure 1.8. Properties of some selected liquid and gaseous biofuels are also given in Tables 1.3 and 1.4.

Table 1.3: Properties of some liquid biofuels [90].

Table 1.4: Properties of some gaseous biofuels [90].

1.3.4 Current status and future projections for biofuels

Over the last decade, global first-generation biofuel production from sugars, starches and vegetable oils has been increasing rapidly. Production of these biofuels has also been extensively investigated, and the production methods have proved successful in some parts of the world such as USA, Brazil, and China [15, 59, 91]. In the US, for example, between 2000 and 2009, bioethanol production increased from 16.9 to 72.0 billion litres and is mandated to increase to 136 billion litres by 2022 while biodiesel production increased from 0.8 to 14.7 billion litres [92]. Globally, approximately 33.3 million ha (Mha) of land under production of biofuels in 2008 may increase to as much as 82 Mha by 2020 [92]. The USA are the world's largest bioethanol producer, and this accounts for 99% of their biofuel for road transport while the EU is so far the world's largest biodiesel producer, and uses considerably more biodiesel than bioethanol [93]. Between 1992 and 2007, production of biodiesel in the EU has grown significantly (36% per annum) [19]. Biofuel consumption in road transport has been increasing in recent years (Figure 1.5). Between 2005 and 2012, global biofuels (bioethanol and biodiesel) consumption has increased by about 221% (from 777, 605 TJ in 2005 to 2, 498, 870 TJ in 2012 [94].

Table 1.5: Biofuel (bioethanol and biodiesel) consumption in road transport (in TJ) [92].

However, production of first-generation biofuel from food crops has led to growing concerns over their sustainability [70, 78, 95-100]. Some of the issues of concern are:

- Competition with food for their feedstock.
- Land use change.
- Effective CO_2 emission savings limited by high fossil energy input during crop cultivation, and

- High cost of biofuels produced.

These growing concerns on the sustainability of first-generation biofuels have generated intense interest in the production of second-generation biofuels (see section 1.3.3). According to [14], production of second-generation biofuels has the potential to providing benefits over the first-generation biofuels such as:

- Consuming readily available high quantities of lignocellulosic residues and wastes
- Making use of uncultivated (abandoned) - marginal land to produce supplementary non-food dedicated energy crops, and
- Promoting rural development and improving the economic conditions in developing regions depending on feedstock choice and cultivation techniques.

1.4 Biofuels support policies

Over the past decades, the number of countries exploiting biomass opportunities for the provision of energy has increased rapidly and this has been driven by governmental policies in an attempt to reduce oil dependency, increase the share of renewable energies and contribute to a reduction in related global warming and climate change through reduced GHG emissions [89]. Many countries have set ambitious biofuels targets. For instance, the European Directive (*EU Directive 2009/28/EC*) on the promotion of the use of biofuels or other renewable fuels for transport within the EU sets out the objective of 10% for biofuels in transport and also a minimum 35% reduction in GHG emissions to be achieved by biofuels during their life cycle by 2020 and 80% by 2050 below the 1990 baseline [81]. Similarly, in July 2010, the USA *Renewable Fuel Standard* (RFS2) set out the objective of an aggregate of 136.26 billion litres of renewable fuel to be used in transport, and also required producers of advanced and standard biofuels to reduce their life cycle GHG emissions by at least 50% and 20% respectively [92]. The Scottish government has currently, set up the most ambitious climate change goals in the world, with the Scotland Climate Change Act setting targets of 42% emissions reduction by 2020 and 80% by 2050.

1.5 Research aims and objectives

The overall aim of this thesis was to evaluate the potential benefits and/or drawbacks of climate change on the productivity of energy and crops and how this would, in turn affect the GHG emissions reductions of biofuels produced from the crops. A reliable projection of how climate change will affect biofuel production would be of real benefit to policymakers for large-scale biofuels development. The aims envisioned by life cycle thinking using a life cycle assessment (LCA) approach, incorporating crop system modeling to determine crop yields and calculate the impact that climate change will have on the GHG emissions savings from biofuels when they are used as substitutes to conventional petroleum-based fossil fuels under baseline and climate change scenarios. The aims and their associated objectives are summarised as follows:

Aim 1:

To determine the impact of simultaneous changes in atmospheric air temperature (*T*), precipitation (*P*), and carbon dioxide concentration ($[CO_2]$) on energy crops yields (chapter 4).

Associated objectives:

- To calculate grain and biomass yields of corn (C4 crop) under baseline and future climate scenarios
- To calculate grain and biomass yields of soybean (C3 crop) under baseline and future climate scenarios
- To calculate grain and biomass yields of wheat (C3 crop) under baseline and future climate scenarios

Aim 2:

To determine the impact of the resulting yields change on GHG emissions reductions of first-generation biofuels (chapter 4).

Associated objectives:

- To calculate the GHG emissions reductions of bioethanol from corn for both baseline and future climate scenarios
- To calculate the GHG emissions of bioethanol from wheat for both baseline and future climate scenarios
- To calculate the GHG emissions reductions of biodiesel from soybean for both baseline and future climate scenarios.

Aim 3:

To determine the impact of the resulting yields change on GHG emissions reductions of second-generation biofuels (chapter 4).

Associated objectives:

- To calculate the GHG emissions reductions of biomethanol from corn through an integrated biomethanol production process for both baseline and future climate scenarios.
- To calculate the GHG emissions reductions of biomethanol from wheat through an integrated biomethanol production process for both baseline and future climate scenarios.
- To calculate the GHG emissions reductions of biomethanol from soybean through an integrated biomethanol production process for both baseline and future climate scenarios.

The structure of this thesis is summarised in Figure 1.1.

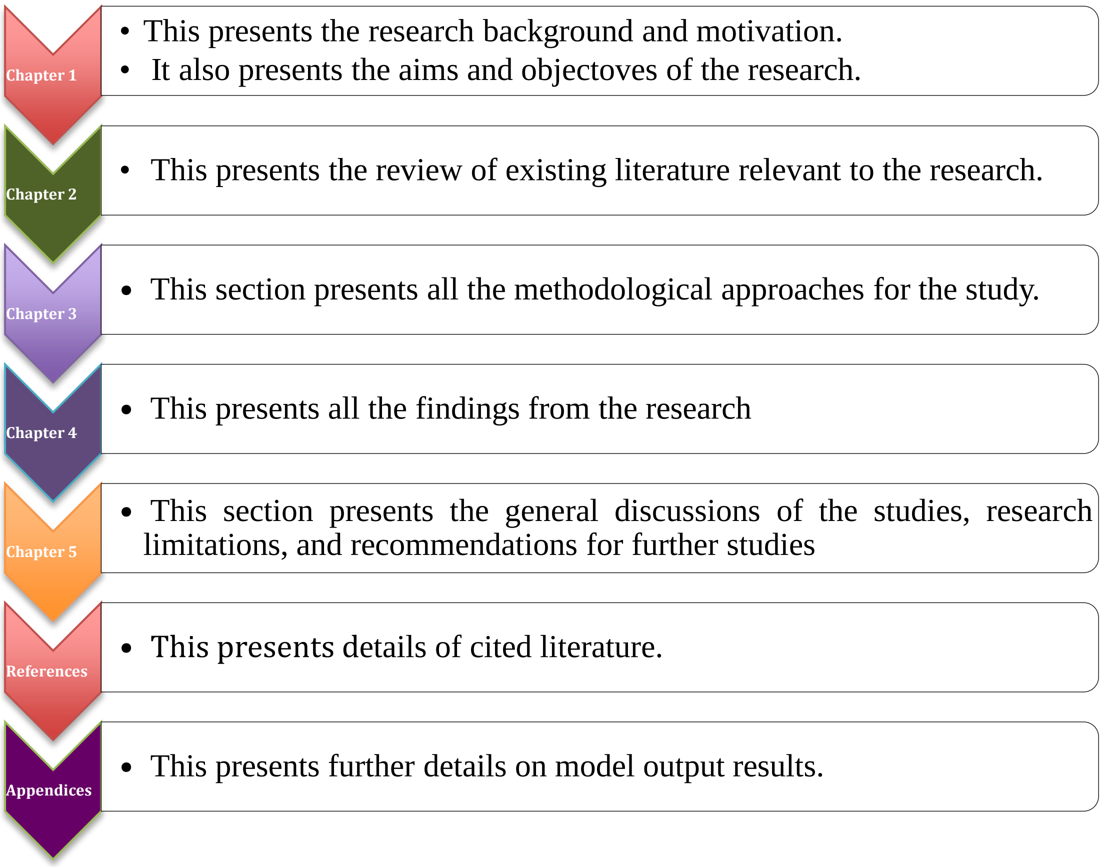

Figure 1.9: Structure of the Thesis

1.6 Summary

This study examined the potential impacts of climate change on energy crop productivity, and the resulting GHG emissions reductions potential of biofuels produced from these crops. The study applied CSM simulation models in conjunction with baseline and projected (modified) 10-yr historical climate data, and LCA models to assess the impact of simultaneous changes in *T*, *P*, and $[CO_2]$ on GHG emissions savings of first and second-generation biofuel technologies under baseline and climate changes scenarios. This was to understand the potential link between climate change and biofuels production since warming is likely to have positive (e.g. due to CO_2 fertilization) as well as negative impacts on crop productivity in rainfed cropping systems, and biofuel production.

Three annual, dedicated energy crops that are widely used for biofuel productions were used in the study using two datasets from the USA and UK as the leading producers of the crops. Corn and soybean were simulated for Gainesville, USA, and wheat was simulated for Rothamsted, UK. However, while it has been recognised that the exact nature and extent of the impacts of climate change on temperature and precipitation distribution pattern remain uncertain, and vary from region to region, it was not possible to carry out the evaluation for all the regions of the world. This lay the foundation for further research on energy crop's response to individual as well as combined changes in *T*, *P*, and $[CO_2]$ using different datasets (regions) and energy crops.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In 2013, the IPCC in its ARF5 [34] concluded that climate change would continue throughout the 21st century. These would, however, pose serious threat on the productivity of energy crops and the climate mitigation potentials of biofuels. This chapter seeks to focus on climate change and its potential impacts on crop productivity and a sustainability assessment of bioenergy production chains through an LCA approach. It is important to consider what is currently known in order to draw out the relationship between crops productivity and climate change and an understanding of the life cycle assessment of biofuels. Further, as outlined in Chapter 1, an important aim of this thesis is to highlight the potential link between climate change and the GHG emissions savings of bioenergy systems. In order to do this, it is necessary to discuss what is currently available in the scientific literature about the implication of individual and/or simultaneous changes in *T*, *P* and *[CO_2]* on energy crops production for biofuels.

2.2 Constraints/critical issues to growth and sustainability of biofuels

The use of biofuels largely depends on the potential of available feedstock sources, which largely depends on climate, land availability and the productivity of dedicated energy crops. Bioenergy is based on resources that can be utilized on a sustainable basis all around the world. In spite of all these potential benefits that can be obtained from the production and use of biofuels from agricultural bioenergy crops, scientific findings have revealed that biofuels can be anything from good to bad depending on the methods used to produce the bioenergy feedstock and process the fuel when compared with fossil fuels [101-106]. Bioenergy from dedicated bioenergy crops could make a substantial contribution to the global bioenergy system if high yields can be sustained.

Hence, sustainability of biofuels is the major challenge in increasing their production and varies significantly between the products and also depends on many factors. These critical issues are sensitive to bioenergy crop yields and the amount of land that could be made available for dedicated bioenergy crops production [107]. These include:

- Land-use change
- Competition with food and feed production
- Use of chemical fertilizers and pest control techniques, and
- Climate change

2.3 Climate change

Climate change is one of the greatest threats to global security and prosperity, and has been attracting scientific and political concerns both nationally and internationally. Sir David King (former UK chief scientist) said "*climate change is the severe problem we are facing today, more serious even than the threat of terrorism*" [108]. The Stern Review on the Economics of Climate Change [109] reported that climate change presents a unique challenge for economics and is the greatest and widest-ranging market failure ever seen. There is an overwhelming scientific consensus that climate change is happening, and it is very likely to be primarily the result of anthropogenic GHG emissions. The increased concentrations of GHG are a direct consequence of human activities leading to global warming by strengthening the natural "greenhouse effect" [110].

In its AR5 [34], the IPCC concluded that the observed increase in global average temperatures since the mid-20th century is 90% due to the observed increase in anthropogenic

GHG concentrations. Atmospheric GHG concentrations have been increasing over the past century compared to the rather steady level experienced during the pre-industrial period. The most important GHG are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and Fluorinated gases (F-gases). There are three main categories of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). A Global Warming Potential (GWP) has been calculated for each GHG as a measure of how long it averagely remains in the atmosphere and how strongly it absorbs energy and contribute to Earth warming. GHG and their GWP are shown in Table 2.1.

Table 2.1: Global warming potential of the major GHG [111].

Similarly, in 2007, the IPCC in its Fourth Assessment Report (AR4) [50] reported that a 70% increase in GHG emissions have been observed between 1970 and 2004 and an increase of between 25-90% has been projected between 2000 and 2030 based on the IPCC's Special Report on Emissions Scenarios (SRES) [112] emission scenarios (A1T, A1B, A1FI, A2, B2, and B1 scenarios) has been projected. The A1 storyline and scenario family (A1T, A1F1, and A1B) describes a future world of very rapid economic growth, rapid introduction of new and more efficient technologies, and the global population that peaks in mid-century and declines thereafter. The three A1 scenario groups are distinguished by their technological emphasis: A1F1 – fossil intensive, A1T – non-fossil energy sources, and A1B – a balance across all sources. The A2 storyline describes a very heterogeneous world, with continuously increasing global population with small technological change. The B1 storyline line describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid ranges in economic structures. The B2 storyline describes a world in which emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2.

The energy, transportation, and agricultural sectors are the major contributors of GHG emissions. For instance, [113] reported that in the EU, the transportation, energy, and agriculture sectors are responsible for more than 20%, 60%, and 9% of GHG emissions respectively. CO_2 is the primary GHG emitted through anthropogenic activities. For instance, in 2011, in the USA, CO_2 accounted for about 84% of all USA GHG emissions compared to 9% and 5% for CH_4 and N_2O, respectively. Global CO_2 emission has significantly increased since 1900. For instance, between 1990 and 2012, global CO_2 emission has increased by about 52% (34.5 in 2012 compared to 22.7 billion tonnes in 1990) [50]. CO_2 emission by the six largest CO_2 emitting countries is presented in Table 2.2.

Global CO_2 concentrations in the atmosphere have been increasing over the past century compared to the pre-industrial era (about 280 ppm). The 2013 concentration of CO_2 (400 ppm) was about 43% higher than in the mid-1800s [34].

Table 2.2: CO_2 emissions by the six largest emitting countries in 1990, 2000, and 2012 (in billion tonnes of CO_2) [3].

2.3.1 Future climate change projections

The IPCC has been established to predict future climate changes in response to human activities. The World Meteorological Organisation (WMO) and the United Nations Environmental Programme (UNEP) established the IPCC, to assess the scientific, technical and socio-economic information that are relevant for understanding the risk of human-induced climate change. A set of descriptions of likely future global GHG emissions was used to project likely future climates resulting from human-induced forcing. For most of these scenarios, there are projections that the emissions and concentrations of the major GHG, such as CO_2, CH_4 and N_2O are expected to increase in the 21st century [114, 115] and this would cause a further increase in global temperatures and many other climatic changes during the 21st century.

Over the 20th century, global surface air temperatures have already increased by 0.8 ^{o}C and are projected to increase by 1.4 – 5.8 ^{o}C during the 21st century [3]. Figure 2.1 presents the multi-model global averages of surface warming (relative to 1980-99) for the scenarios A2, A1B and B1.

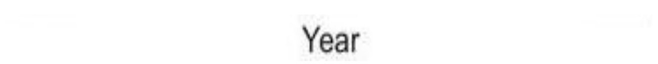

Figure 2.1: Multi-model averages and assessed ranges for surface warming [50]

According to the IPCC's AR4 report [50], all models indicate global increase in precipitation in the tropics and decrease in subtropics. Global increase in the mean water vapour, evaporation and precipitation are predicted to occur. Tropical and high latitude areas are projected to experience increase in intense precipitation events. In most subtropical and mid-latitude areas, precipitation intensity is projected to increase but with longer period between rainfall events. Mid-continental areas are also predicted to stand a greater risk of drought in the future warm climate. Figure 2.2 below shows the projected patterns of precipitation changes.

Figure 2.2: Projected patterns of precipitation changes [50].

Given the long lifetime of GHG in the atmosphere and their role in progressive warming of the Earth's climate, stabilizing GHG concentrations in the atmosphere at any level would require large reductions of global GHG emissions from current levels. In 2005, under the first phase of Kyoto protocol about 191 countries (e.g. Australia, Iceland, Norway and Croatia) had committed towards reducing their atmospheric CO_2 emissions [1].

In 2012, when the first phase of the Kyoto protocol ended, the group of industrialized countries (e.g. United Kingdom, Germany, Belgium and Denmark) committed to the Kyoto target had their 4.7% global CO_2 reduction target met for the period 2008-2012 relative to the 1990 base period.

2.3.2 Climate change impacts on Agriculture

The agricultural sector would be the most vulnerable to climate change [29, 116]. Therefore, climate change would have significant impacts on agricultural production of bioenergy crops because of the high dependence of agriculture on the climate. Most studies of the impacts of changing climate on agriculture indicate that there will be negative effects over the next century. These could be impacted through:

- High temperature effect on crop growth and productivity, increased occurrences of pest and diseases, and altered water availability.
- Altered rainfall patterns.
- Enhanced frequency of extreme weather events
- Enhanced CO_2 concentration in the atmosphere, and
- Sea level rise and frequent flooding.

2.3.2.1 Effect of high temperature on crop production

Agricultural energy crops production will be affected by the projected increase in the mean temperature towards the end of the 21st century [24, 30, 31, 35-37, 117, 118]. Temperature is a key determinant of the crops yield. High temperatures are expected to enhance high crop yield in the tropical regions due to high rates of biochemical reactions taking place in the crops resulting from high temperature. However, when the temperature exceeds the optimal limit for plant growth and development, crops negatively responds leading to decrease in net growth and yield. Energy crops are highly sensitive to atmospheric and/or soil temperature changes at various stages of their life cycle. For instance, [119] reported that yields are sensitive to brief episodes of hot temperatures if they coincide with critical stages of their development (e.g. when high temperature episode coincide with time of flowering).

In recent years, energy crop's response to high and fluctuating temperatures have been extensively studied [120-122]. Research findings have also shown the importance of temperature variability for annual crops yield [119]. Although crop yield is more sensitive to precipitation than temperature, the predicted increase in the mean seasonal temperatures of 2-4 ^{o}C could reduce annual crops yield.

2.3.2.2 Effect of elevated atmospheric CO_2

Elevated atmospheric CO_2 can enhance photosynthesis and improve crop yield. Improved water uptake efficiency is achieved under increased CO_2 concentration. However, these all depends on the nature of the plant and other factors such as pest and diseases, nutrients and water availability [123-126]. C3 crops (e.g. rice, wheat, and soybeans) are more affected by increased atmospheric CO_2 than C4 crops (e.g. maize, millet, and sorghum). Therefore increased crop productivity can be expected from C3 crops compared to C4 crops under increased CO_2 concentration. From a photosynthetic point of view, C3 crops first incorporate CO_2 into a 3-carbon compound during photosynthesis. The crops use RUBISCO (ribulosediphosphate carboxylase) enzyme for CO_2 uptake from the atmosphere to produce phosphoglycerate. While C4 crops first incorporate CO_2 into a 4-carbon compound (oxaloacetate), using PEP Carboxylase (phosphoenol pyruvate carboxylase) enzyme.

2.3.3 Study of climate change impact on agriculture

A literature survey revealed that a number of tools have been applied to understand the potential impacts of climate change on agriculture. These include:

- Global climate models
- Controlled field experiments
- Integrated climate – crop models
- Statistical analyses of past climates

Experimental data and/or crop growth simulation models are used to determine the potential impacts of climate change on crop yield based on understanding the drivers of climate change. Large uncertainties in understanding different crop simulation models have been developed and are now widely used to evaluate the potential impacts of different variables in relation to climate change on crop yield. Some of these models are given in Table 2.4. Because of their huge importance in agriculture and sensitivity to climate change, current modelling studies focus on the impact of different climate parameters on cereal crops production. Some model projections include [116]:

- Changes in crop yields due to seasonal changes in climate
- Changes in production potential in relation to yield, available agricultural land, and lengthened/shortened growing seasons
- Crops response to atmospheric compositions, such as CO_2 and temperature

Table 2.3: Crop models used in the study of climate change impacts on crops [127].

The impact of climate change on cereal crops production is mostly concerned with the climatic parameters such as, precipitation, temperature, and atmospheric CO_2 concentrations.

Many recent studies [16, 41] have investigated the impacts of present and future climate change on the yield and yield components of agricultural crops.

2.4 Study of sustainability of bioenergy systems

Development of sound and effective environmental policies and strategies requires proper and reliable scientific basis. To attain the environmental goal of sustainable development, a number of methods (e.g. environmental performance evaluation, environmental auditing, risk assessment, and environmental impact assessment) have been used as environmental management tools in recent times, to study the environmental aspects and impacts of a product [128]. The following sections provide an overview of some of these tools and their applications in environmental management relating to biofuels production.

2.4.1 Life Cycle Assessment (LCA)

As technologies for the conversion of biomass to biofuels differ in their feedstocks requirement, feedstocks handling (pre-treatment), conversion processes as well as energy and materials inputs, they exhibit a range of life cycle energy and environmental performances.

Life cycle assessment (LCA) often referred to as "cradle-to-grave", is a methodology for assessing the environmental performance of a product. The life cycle concept is used to evaluate the entire life cycle of a product from raw material extraction and acquisition, through energy and material production, to use and end of life treatment and final disposal [129]. LCA can be defined as:

"A process to evaluate the environmental burdens associated with a product by identifying and quantifying energy and materials used and wastes released into the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements" [130].

A complete LCA process includes stages of collecting data to produce an inventory of inputs and outputs to a process. The data may come from a variety of sources, and indeed may reside in a database within commercially available packages. The data will largely be quantifiable and thus form an objective basis for the interpretation stage. Interpretation on the other hand, is subjective in that the outputs will often be in terms of a set of parameters, which are not directly comparable, for example, resource consumption, gaseous emissions, and heavy metal release. Whilst there remains insufficient detail of the relative or absolute impact of these parameters on the environment, or where they impact in different locations, pathways or receptors, a direct comparison is impossible and so any interpretation of the overall impact is likely to require judgement and thus is subjective.

In the late 1920s, forms of LCA were first used in the USA for defining corporate environmental strategy, and were later used by the government agencies as an aid for developing public policy towards promoting sustainable development in the 1970s [128]. Similarly, in the late 1990s, LCA emerged as a globally accepted standardised environmental management tool in the form of ISO 14040 series [128].

Today, LCA is widely used to compare the environmental performance of two functionally equivalent products, or in some cases to assess the environmental performance of a single product. A generally accepted framework for performing LCA involves a phased approached comprising of four interrelated components otherwise called ‘4 Is’ (see Figure 2.3).

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Figure 2.3: The interrelationship between the four phases of LCA [128]

Over the years, the LCA methodology has been used globally as a valuable tool for decision making towards sustainability to evaluate the environmental and energy performances of different energy crops. However, there is general lack of local data in developing countries to improve the availability of data for LCA studies [131].

[78] evaluated the energy balance and GHG emissions of different biofuels and biorefinery systems using an LCA methodology. The authors concluded that the determination of energy balance and environmental emissions from bioenergy systems is complex, and different combinations of feedstocks, conversion routes and biofuels; end-use applications and methodological assumptions lead to a wide range of results. [72] analysed the production of biofuels from agricultural crops in northern Europe based on area of cultivation and energy efficiency and GHG emissions. Results show that direct land-use changes have significant

impact on GHG balances for all biofuels studied. [72] also reported that the design of the production system may have significant impact on the energy and environmental performances of the biofuels. For example, whether or not renewable and fossil fuels are used in the conversion processes.

[132] evaluated the energy and environmental performance from a cassava-based bioethanol production system. Results show that high-energy consumption comes from the ethanol conversion stage, which accounts for 78% of the total energy usage. [133] performed an energy and environmental evaluation of biodiesel production from palm oil finding that the highest energy consumption in the biodiesel (palm oil methyl ester – PEM) production system came from the transesterification process and a net energy ratio (NER) of 2.5 could be achieved. NER is a term used to describe the relationship between energy output of a system and the energy inputs needed to operate it. A comprehensive review of LCA studies for different transportation fuels including fossils and biofuels was conducted by [134]. Fuels reviewed include conventional gasoline (CG), conventional diesel (CD), liquefied petroleum gas (LPG), compressed natural gas (CNG), wheat-derived ethanol (E-W), corn-derived ethanol (E-Co), cassava-derived ethanol (E-C), sugarcane-derived ethanol (E-S), rapeseed-derived biodiesel (BD-R) and soybean-derived biodiesel (BD-S). It was found that LPG and CNG have slightly lower life cycle fossil fuel use and GHG emissions than CG and CD. It was also found that bioethanol from different feedstock varies largely in terms of life cycle fossil fuel use and GHG emissions. E-Co and E-S seem to be much better choices compared with CG. Both BD-R and BD-S can offer substantial benefits in terms of life cycle fossil fuel use and GHG emissions. Replacing petroleum-based fuels with CNG or biofuels can reduce life cycle petroleum use significantly.

[131] carried out a cradle-to-farm gate Life Cycle Assessment (LCA) to compare the environmental impacts and energy and water demand of rapeseed (*Brassica napus* L.) and

sunflower (*Helianthus annuus* L.) as potential crops for first-generation biodiesel production, in Chile. They evaluated the effects of nitrous oxide (N_2O) and land use change associated with the crops production. They found that rapeseed production has a better environmental performance, lower water consumption, and lower energy demand compared to sunflower production. They also found that mineral fertilizers caused the highest environmental impact in terms of GHG emissions in both crops studied. [135] integrated LCA and LCC analyses to assess the environmental and economic performances of sugarcane based bioethanol in Brazil compared to gasoline, under two different scenarios: base case and future case scenarios. The base case scenario represents bioethanol production from sugarcane plus electricity generation from bagasse, whilst the future case scenario represents bioethanol production from both sugar cane and bagasse + electricity generation from wastes. Results showed that less GHG is emitted in the case of the base case scenario while the future case scenario is more economically attractive.

The choice of system definitions and boundaries, functional unit, reference system as well as allocation methods are crucial in any LCA studies (see [78, 136-138]). [5] demonstrated and quantified the significant effects of methodological choices on the GHG and energy balance of biofuels based on a case study for the production of bioethanol from wheat in the Swiss context. They also demonstrated and quantified the effects of fuels blend and choices regarding vehicle/fuel performance. They found that the allocation of impacts between the co-products, the type of reference systems, the type of land-use change, and the type of fuel blend were all responsible for the large variation in the net GHG emissions of the bioethanol from wheat for transportation. An overview of the most important steps in calculating the energy and GHG balances of bioenergy systems producing electricity, heat and transportation biofuels from biomass residues or crops has been provided by Cherubini [137]. The author discussed the key methodological assumptions of LCA such as functional unit, allocation, reference system, system boundaries, and some of the factors affecting final outcomes. The factors considered are direct and indirect land-use change, organic carbon pool, N_2O and NH_4 emissions from soils, and effects of residue removal.

Few LCA studies on second-generation biofuel production systems are currently available [78]. [139] compared the technological features and life cycle environmental impacts of different lignocellulosic bioethanol conversion technologies finding that the conventional fossil fuels use reduction potential as well as GHG emissions reductions vary among the conversion processes. However, the bioethanol conversion technologies offered better environmental benefit in terms of GHG emissions reductions compared to gasoline. The environmental impacts associated with second-generation bioethanol from flax shrives (co-product from pulp fibre production) [140], *Brassica carinata* [141], poplar biomass [142] and switchgrass [79] production and use in a flexi fuel vehicle (FFV) compared with conventional gasoline throughout their whole life cycle have been recently studied. Ethanol blended with gasoline (E10, E85 and E100) was evaluated, and studies show that cellulosic biomass feedstocks are promising options to making ethanol. They concluded that agricultural activities related to feedstock production were identified as notable contributors to the environmental performance. They also reported that there is the need for high yielding varieties, decline in the use of inorganic chemical fertilizers, and reduction in tillage in order to reduce these impacts.

In order to assess the environmental benefits from the utilization of biofuels compared to fossil fuels, whole life cycles have to be determined. According to [78], LCA of biofuels largely depends on the type and management of feedstock, conversion routes, choice of location, by-products and co-products allocation, system boundaries, how the fuel is used, and reference energy system with which the biofuel chain is compared. An overview of the energy flow and the emissions for the evaluation of biofuels is shown in Figure 2.4. However, the overall critical point of how biofuel production influences climate is the type of biomass feedstock because it determines the biomass (energy) yield per unit of land, the use of fertilizer [143].

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Figure 2.4: An overview of energy flow and emissions for all process steps in the LCA of biofuels [88]

2.5 Carbon footprint of bioenergy systems

Although the LCA methodology has been extensively used as a tool for assessing the environmental performance of bioenergy systems from dedicated energy crops, mainly focusing on net energy balance and GHG emissions [4, 5, 7, 9, 13, 70, 74, 79, 101, 144-154], its practical application is not always straight forward. Even LCA studies on similar products may yield different results, particularly when studying agricultural systems for which the parameters vary depending on their specific conditions [99, 100, 155, 156] feedstock types and the cropping systems, design of the specific production system, data quality, assumptions, methodologies and system boundaries, and choice of allocation methods [8, 78, 137, 157-160]. Other factors are the selection of impact categories, the choice of reference system, direct and indirect land-use change, treatment of biogenic carbon [161-163], and the effect of above ground biomass removal from soils [138, 164, 165]. For example, findings from [99], [166], and Wang [167] indicate that calculations of the net energy value (NEV) of biofuels are highly sensitive to assumptions about both system boundaries and key parameter values.

2.6 Critical Issues in LCA of Biofuels

The choice of allocation methods in LCA studies of bioenergy systems has always been one of the major critical issues essential for LCA outcomes, especially for global warming potential [55, 167]. LCA studies require that environmental flows be attributed among products when a process yields multiple products through a value-based allocation (e.g. by economic value, energy content, or mass), or by crediting the production system through the displacement (sometimes referred to as substitution) method for co-products. The choice of co-product method can significantly influence the LCA outcomes of biofuel particularly when economic value is used as a reference. Substitution of avoided burden seems to be the most popular allocation method in practice, followed by partition based on mass, energy, and economic values. Most LCA studies have shown some conflicting LCA outcomes when using different allocation methods, in particular, the use of energy partitioning, mass partitioning, economic values as opposed to physical properties as a basis to allocate burdens from multi-output processes, substitution of avoided burden [22, 168], and including or excluding biogenic emission of CO_2 in the outcome of the LCA results [169]. For instance, [135] reported that the application of economic allocation leads to increased global warming potential (GWP) when replacing gasoline by ethanol fuels, while reduction of GWP is achieved when mass/energy allocation is used as well as in the system where biogenic CO_2 is excluded. Mass and energy allocation methods were used in the study of corn bioethanol [170] and findings are that in the mass allocation method, the co-product credit was equal to the energy input of all production steps leading to creation of the co-product multiplied by the relative weight of the co-product. In the energy allocation method, the co-product credit was the amount of inherent energy (low heat value) within each product assuming complete combustion at 90% boiler efficiency. [170] employed market value allocation method whereby the co-product credit was equal to the relative value of each of the products such as ethanol and Distilers Dried Grains and Solubles (DDGS). The idea behind this market value allocation is that the actual cause for the production is the economic value of the products. An allocation problem can be avoided through a system expansion method. In some studies expanding the product system to include additional functions is applied [135, 157]. For example, [70] employed the system expansion approach in the study of soybean. One of the co-products of soybean is soybean meal. Soybean meal is used in animal feed and assumed to be able to replace DDGS, which is also used in animal feed.

Similarly, some authors have pointed out the importance of including direct and/or indirect land use change in the LCA of bioenergy systems [171]. The importance of making LCA assumptions with or without farm emission of N_2O has been cited in the literature [164, 172]. [164] showed that the effects of N_2O emission could account for as much as 60% of the greenhouse gas footprint of a biofuel system. A number of recent studies have also focused on testing the effect of direct and indirect land use change on the LCA of bioenergy systems.

The expansion of land used for bioenergy crop production causes variable direct and indirect GHG emissions and other economic, social and environmental effects [173-175]. Direct land use change (dLUC) occurs when new agricultural land for cultivation of bioenergy crops displaces prior land use, for example the conversion of forest and/or grassland into corn plantation [138], while indirect land use change (iLUC) can be illustrated as an increase in demand for forest log and forest residues in one place due to increased logging activities or deforestation in another place [176]. Land use change has an impact on global warming, as it can be accompanied by sometimes, large changes in GHG emissions from soils [177]. [100] showed that including GHG emissions from dLUC and iLUC may change a net GHG benefit into a net cost. One possible solution for this issue is to shift from attributional to consequential LCA, in which consequences are specified at the functional unit level.

[178] reported that methodological challenges still exist in the LCA of bioenergy systems regarding the assessment of direct and indirect land use change emissions. According to [179], the problem of iLUC emissions in the GHG emissions savings due to substitution of fossil fuels by biofuels can be solved by a pay- back time indicator, as used by several authors (e.g. [100, 177, 180, 181]. The payback period is the period over which the annual GHG savings due to substitution of fossil fuels by biofuels equalize GHG emission from land use change. However, [182] argue that LUC GHG emissions may have a smaller contribution to the overall biofuel life cycle than previously thought.

Crop yield has also been cited as one of the critical factors that could influence the LCA of bioenergy systems, particularly regarding net GHG emissions savings [143, 183, 184]. Yield increases have the potential to offset effects of indirect land use change [183]. Agricultural inputs such as fertilizer, seed, herbicides/pesticides, and machinery require fossil fuel in their production process. Fossil fuels are also required for field operations and application of farm inputs. There is growing attention [16, 40, 185] regarding the importance of bioenergy crops yield in ability to produce biofuels mainly focusing on the impact of crop management practices, soil, and climate change and its variability. Past studies by [23] indicate that some of the basic responses to climate change can be individual or simultaneous changes in temperature (*T*) and precipitation (*P*). Studies by [186] indicate that precipitation is one of the leading factor affecting crop yields. In addition, temperature changes have been shown to affect crop productivity [187]. Similarly, studies that have monitored the influence of carbon dioxide concentration on crops have focused on the impact of increased atmospheric concentration of CO_2 on growth and yields of energy crops [125, 188]. In [126] the impact of elevated CO_2 on crop productivity was analysed and suggested that it may aid crop productivity due to its fertilization effect. According to [189], the rates of plant growth and development would continue to increase due enhanced metabolic rates at higher temperatures, combined with increased carbon availability. Thus, there is potential for interactive effects of multiple environmental factors such as T, $[CO_2]$ and P on the response of plants.

[160] studied the impact of agricultural practices on bioethanol production and found that crop rotation used in corn production could make a significant difference in corn yields and net GHG emissions. [16] simulated the impact of irrigation, nitrogen fertilizer, and planting date on three maize cultivars (Dekalb DKC 6172, Pioneer 31D58, and Pioneer 31G98) for bioethanol production and found that crop management practices had a significant impact on ethanol feedstock yield and NEV. Similarly, [41] evaluated the effects of soil variability on the NEV of ethanol produced from maize in four different regions of South-eastern USA using the CERES-Maize model linked with life cycle bioethanol NEV calculations. Results show that soil variability significantly affects the NEV of bioethanol NEV for all the regions.

Given the global concern regarding the vulnerability of bioenergy crops to climate change, there is growing interest on the potential link between biofuel production and climate change

[16, 40, 185]. Assessment of these potential impacts for instance, on GHG emissions savings requires the use of climate change models, crop system models, such as the DSSAT-CSM, combined with LCA models. However, few studies are currently available in the literature and most are based on the security of feedstock supply and/or on the NEV. For example, studies by [16] show that NEV of bioethanol produced from maize (corn) shows sensitivity to climate variability, with increases during La Nina years and decreases during El Nino years for maize grown under both rain-fed and irrigated conditions in Mitchel County, Georgia, USA. [190] also investigated the impact of wind damage on biofuel feedstock production, and assessed the effect that a future potential increase in tropical cyclone intensity would have on energy security, rural development and climate change mitigation measures in the Philipines in 2050. Results suggest a modest decrease in biofuel feedstock productivity that is shown to affect the Philippine's policy goals. However much remains to be understood regarding the potential link between extreme climate changes and the GHG emissions reduction of biofuels. [40] studied the impact and implications of weather, climate, and soil variability on switchgrass production in the south-eastern USA using Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model. Simulations were performed under different climate and land use scenarios using 1950s, 1960s, and 1980s Tennessee River Valley regional weather data. Their study showed that the average annual simulated switchgrass yield across the region was significantly higher for the 1950s and the 1980s climate than for the 1960s climate due to climate change. However, future climatic changes were not included in the study. [191] studied how climate change will impact future production of switchgrass, corn, sorghum, winter wheat, and soybean in the central United States. They used a combination of National Centre for Atmospheric Research (NCAR) and climate change scenarios, regional climate (RegCM), and crop productivity models (EPIC) to predict the changes in crop yields. CO_2 fertilization effects were also evaluated in the study. The authors found negative impacts on crops yield from increased temperatures, and positive impacts from increased precipitation and atmospheric CO_2. [192] studied the potential distribution of bioenergy crops in Europe under present (1961-1990) and future climate (2020, 2050, and 2080). They used outputs from four different global climate models (HadCM3, CSIRO2, PCM, and CGCM2) to predicts the potential climatic distribution of oil crops (oilseed rape, linseed, field mustard, hemp, sunflower, safflower, castor oil, olive, and groundnut), cereals (barley, wheat, oat, and rye), starch crops (potato, sugar beet, Jerusalem artichoke, and sugarcane), and solid biofuel crops (cardoon, sorghum, kenaf, prickly pear, whole crop maize, reed canary grass, miscanthus, and eucalyptus) under four IPCC emission scenarios (A1F1, A2, B1, and B2) [112]. They used simple elevation and climatic data (climatic requirements – maximum and minimum temperature, maximum and minimum precipitation per annum) for each crop to determine (using a simple program written in FORTRAN) whether each crop could grow in each grid cell under current and future climate. However, no account of yield was taken in their study. They found that all models and scenarios highlighted the vulnerability of southern Europe to climate change. [193] evaluated the effects of global climate change on the land availability for liquid biofuels production in Brazil using PRECIS model projections for temperature and precipitation at a 50 km x 50 km square resolution for the 2071-2100 period to analyse the impact of climate change on the geographical distribution of sugarcane (for bioethanol), and soybean, dende nuts, castor beans, and sunflower (for biodiesel). The study followed a methodological procedure described by [192] given the projections for maximum and minimum temperature for 2080, 2090, and 2100 under A2 and B2 scenarios. They found that biofuel production in the region would suffer from changes in the climate in those regions. Other climatic variables such as atmospheric CO_2 concentration and precipitation were not considered in their study.

[194] also assessed the potential impacts of climate change on wheat production as a biofuel crop in southern Saskatchewan, Canada, using DSSAT-CSM to simulate biomass and grain yield under three climate change scenarios (CGCM3 with the forcing scenarios of IPCC SRES A1B, A2 and B1) [112] in the 2050s. Compared with the baseline, precipitation was projected to increase every month under all three scenarios except in July and August and in June for A2, when it is projected to decrease, while annual mean air temperature was projected to increase by 3.2, 3.6 and 2.7 °C for A1B, A2 and B1, respectively. The model predicted increases in both biomass and grains yield by 28, 12 and 16% without the direct effect of CO_2 and 74, 55 and 41% with combined effects (climate and CO_2) for A1B, A2 and B1, respectively. Similarly, [195] evaluated the effects of future environmental changes of CO_2 enrichment and water stress on the growth and biodiesel production of *Jatropha curcas* under two levels of CO_2 concentration (ambient and elevated) and three water regimes (well watered, moderate drought, and severe drought). Elevated CO_2 was found to enhance biomass accumulation of *J. curcas* by 31.5, 25.9, and 14.4% under well-watered, moderate drought, and severe drought treatments, respectively. However, no study is currently available on the impacts of climate change on GHG emissions savings of biofuels [196].

2.7 Summary

There is consensus that increased atmospheric GHG concentrations are warming the world's climate, which is expected to continue even if the current concentration level is maintained. Climate change, which is increasingly recognized as one of the greatest challenges of our time will have far reaching consequences on so many sectors such as health, transport and agriculture. Climate change and sustainable production of biofuels from dedicated energy crops intersect in the agricultural sector, which is highly climate-sensitive. Most research on the impact of climate change focuses mainly on agricultural productivity (food security) due to its sensitivity to weather and climate. Climate change is expected to have negative as well as positive impacts on agricultural productivity depending on so many factors such as the nature of the crop, region, and warming scenarios.

At the same time it has been accepted with accumulating evidence that bioenergy from energy crops could help in reducing AGW. However, bioenergy production also relies on agricultural production of dedicated energy crops. Thus, due to the vulnerability of agriculture to weather and climate variable such as temperature, precipitation, and CO_2, climate change will therefore have substantial impacts on energy crop yields by the end of the 21st century.

Numerous studies have been conducted to estimate the impacts of warming on agricultural productivity in terms of food production. Few studies are currently available on the impact of warming on energy crops productivity for bioenergy production, most of which only focuses on either feedstock supply and/or NEV. Novel estimate of the link between climate change, energy crop yields, and net GHG emissions savings resulting from the production and utilization of biofuels as alternatives for conventional fossil fuels is therefore very crucial for coherent decision-making processes regarding biofuels, agriculture, and climate change polices that would provide strategic direction on what to prioritize. It is envisaged that this thesis will contribute to a better understanding of how future climate change would impact agricultural production of energy crops for biofuels production.

Assessment of these potential impacts requires the use of climate change models, cropping system models such as the DSSAT-CSM combined with LCA models. The methodology (presented in the next section – Chapter 3) was underpinned by life cycle thinking.

CHAPTER 3: RESEARCH METHODOLOGY

3. 1 Introduction

This Chapter describes the design of the modelling approach required to achieve the research aims and objectives as stated in Chapter 1. A comprehensive and integrated life cycle approach was employed. The methodology couples climate change projection to CSM modelling, which was then linked to LCA modelling. Potential impacts of future climate change were calculated for different scenarios of climate change. There are three main components to the research: firstly, climate change scenarios were constructed in the DSSAT-CSM [197, 198] based on changes in daily climate variables (temperature, precipitation and atmospheric CO_2); secondly, the potential effects of the combined changes in temperature (*T*), amount of precipitation (*P*), and atmospheric CO_2 concentration (*[CO_2]*) on grain and biomass yields of energy crops (corn, soybean, and wheat) were calculated; and thirdly, the effects of these yield changes on life cycle GHG emissions savings resulting from production and use of first and second-generation biofuels as alternatives to conventional fossil fuels were also calculated. The flowchart that summarizes the different studies carried out is shown in Figure 3.1.

Projected changes in energy crops yield were calculated using the DSSAT-CSM model with the observed climate data (1981-1990) and projected climate change scenarios. The GHG emissions savings were calculated using an LCA approach according to the ISO 14044 standard [128] using yield outputs from the DSSAT-CSM model and life cycle inventory data from the ecoinvent database [199].

This methodology is unique in its ability to cover all the process chains from climate change projection, bioenergy crop production, bioenergy conversion, bioenergy distribution, and biofuel-based net life cycle GHG emissions reductions from conventional fossil-based fuels replacement.

Section 4.2

Investigation of the impacts of climate change (simultaneous changes in temperature, amount of precipitation, and CO_2 concentration on grain and biomass (straw) yields of C4 crop (corn) and C3 crops (soybean and wheat) as feedstocks for biofuels production (Chapter 4, section 4.2).

⇩

Section 4.3

Investigation of the potential impacts of the resulting grain yields change from section 4.1 on the life cycle GHG emissions savings of first generation biofuels: bioethanol from corn and wheat, and biodiesel from soybean (Chapter 4, section 4.3).

⇩

Section 4.4

Investigation of the potential impacts of the resuling changes in both grain and biomass (straw) yields on the life cycle GHG emissions savings of second generation biofuels: integrated biomethanol and integrated biolectricityfrom corn, soybean, and wheat (Chapetr 4, section 4.4).

Figure 3.1: Flowchart showing summary of studies

3. 2 Energy crops yield calculation (Aim 1)

3.2.1 Cropping system models

The DSSAT-CSM model [197, 198] was used to investigate the effect of simultaneous changes in *T*, *P*, and *[CO_2]* on corn, soybean, and wheat grain and biomass yields. The

DSSAT-CSM is a software application program that comprises crop simulation models for simulating the growth of over 27 crops and is supported by database management programs for soil, weather, and crop management and experimental data and has been validated for over 100 different countries worldwide (see [197]). DSSAT-CSM simulates growth, development and yield of a crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time. DSSAT-CSM is structured using the modular approach described by [200] and [201]. The primary modules for DSSAT-CSM are for weather, soil, plant, the soil-plant-atmosphere interface, and management components. Further details are described in [197].

The DSSAT model comprises the CERES-Maize, CERES-Wheat (Crop Environment Resource Synthesis-Maize and Wheat) and CROPGRO-Soybean (Crop Growth-Soybean) models for simulating the growth and yield of corn, wheat, and soybean, respectively as a function of the soil-plant-atmosphere dynamics, and they have been used for many applications such as regional assessments of the impact of climate variability and climate change and energy crops production [194, 202].

The CERES-Maize, CERES-Wheat and CROPGRO-Soybean models are predictive, deterministic models, which stimulate physical, physical, and chemical processes in crop and its associated environment. The models are constructed to simulate primary crop processes as a function of weather, crop management practices, and soil conditions. CERES-Maize derives daily rates of crop growth (Plant Growth, Regulator, PGR, g plant^{-1} d^{-1}) as the product of light intercepted by the canopy (Incident Photosynthetically Active Radiation, IPAR, MJ plant^{-1} d^{-1}) and radiation use efficiency (RUE, g MJ^{-1}) [202]. The rate of development in CERES-Maize is controlled by temperature (growing degree-days: GDD). Daily crop growth is calculated by converting intercepted photosynthetically active radiation (PAR) into crop dry matter with a crop-specific RUE parameter [197].

The CERES-Maize, CERES-Wheat, and CROPGRO-Soybean models require a minimum data set for model operation. The contents of such a dataset are shown in Table 3.1. The dataset encompass data on the site where the model is to be applied, daily weather during the growing cycle, the characteristics of the soil at the start of the growing cycle or crop sequence, and the management of the crop (e.g. seeding rate, fertilizer applications, and irrigation).

The models require detailed farm level management practices, soil profiles, genetic coefficients describing the crop cultivar, and daily meteorological conditions (precipitation, solar radiation, atmospheric concentration of CO_2, and maximum and minimum temperature). They simulate physiological crop responses on a daily basis as a function of climate factors (daily maximum and minimum temperature, precipitation, and solar radiation), soils, and crop management practices (cultivar, planting date, row spacing, plant population, and planting depth). The models have been applied extensively in many different parts of the world for climate change applications [41, 118, 203-209]. These models compute important biophysical and biochemical processes, like photosynthesis, respiration and transpiration or the dynamics of carbon and water at the leaf-level and are therefore able to simulate the effect of increasing temperatures, changing precipitation and elevated atmospheric CO_2 concentration on crop development and yield [25].

Table 3.1: Contents of minimum data sets for operation and evaluation of the DSSAT-CSM model [197].

3.2.2 Climate data and climate change scenarios

Any climate change scenario must adopt a reference baseline period from which to calculate changes in climate. This serves as the base on which data sets that represent climate change are constructed. This study adopted the 1981-1990 (10-year) baseline period from the standard 30-year (1961-1990) normal baseline period as defined by the World Meteorological Organisation (WMO), which provides a standard reference for climate change impact studies [50]. Observed 10 year (1981-1990) climate data were obtained for Gainesville, USA (29.6514^o N, 82.3250^o W) and Rothamsted, UK (51° 48' 00" N, 00° 22' 00" W), representing daily minimum/maximum air temperature and precipitation. The 10-year observed daily climate data was used as baseline climate scenario. This scenario looked at simulations derived from the unmodified observed climate data.

Based on the climate change predictions given in Tables 3.2 and 3.3, climate change scenarios were generated for each study site using the observed climate data. Scenarios were created using a combination of changes in temperature, precipitation and atmospheric CO_2. Projections were made using the "environmental modification" section of the XBuild module in DSSAT-CSM model, which generate climate change scenarios using various combinations of temperature, precipitation, and atmospheric CO_2 levels (Figure 3.2). Daily changes in the climate variables were applied to the observed daily climate records. The atmospheric concentration of CO_2 was considered as 330 ppm for the baseline period, which is the default value in the DSSAT-CSM software for the normal baseline reference period (1961-1990), which also provides a standard reference for climate change impact studies [50] increasing with +70ppm (400 ppm) +70 ppm x 3 (540 ppm) and +70 ppm x 5 (680 ppm) in the future reference to the baseline concentration [115]. However, in early 2013, atmospheric CO_2 concentrations had increased to about 400 ppm, and is further projected to grow in the future above 660 ppm from the remaining fossil fuel deposits [53].

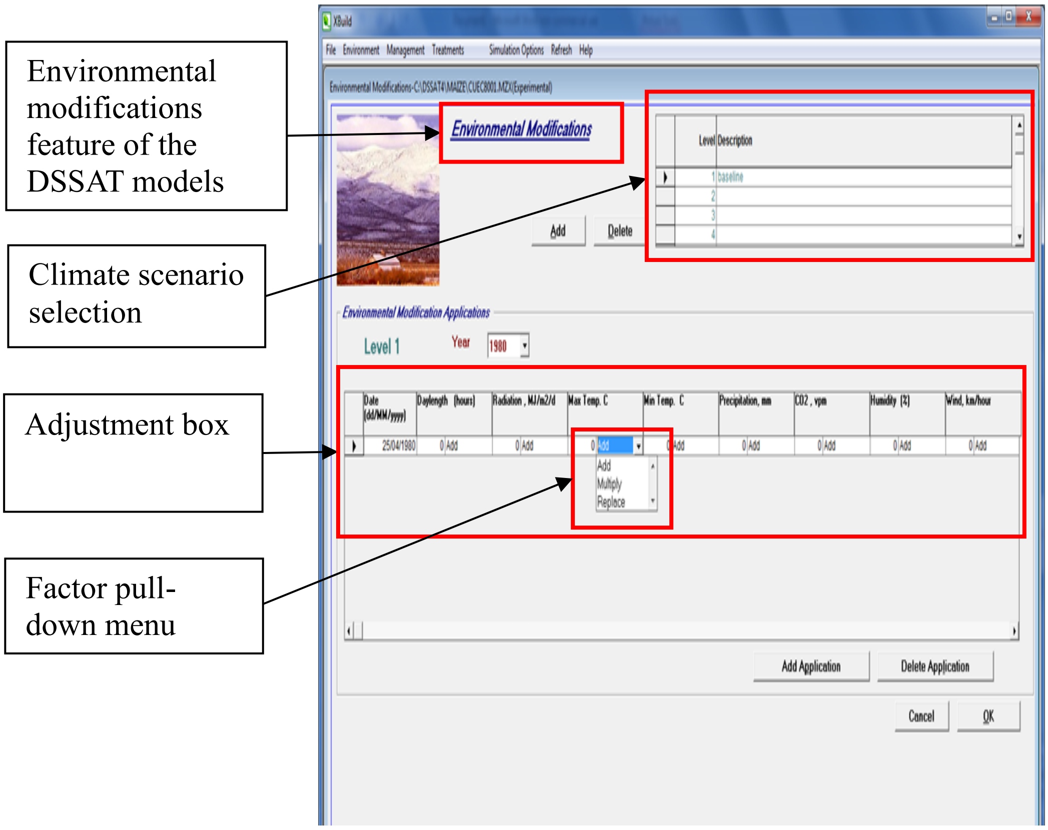

Figure 3.2: Screen shot of environmental modification applications window of the DSSAT model. The factor pull-down menu provides 3 options: “Add”, “Multiply” and “Replace”. For an environmental variable (i.e. minimum and maximum temperature, precipitation, and CO_2), a value was entered in the adjustment box and the type of adjustment was specified using the menu items in the factor pull-down menu.

To assess the effect of changes in climatic conditions on the yield of corn and soybean, 320 different climate change scenarios were provided to CERES-Maize (corn) and CROPGRO-Soybean (soybean) for different temperature, precipitation and CO_2 conditions as shown in Table 3.2. For wheat, 60 different scenarios of climate change were provided to CERES-Wheat for different temperature, precipitation, and CO_2 conditions as shown in Table 3.3.

Table 3.2: Simulated temperature, precipitation, and CO_2 concentration ranges for corn and soybean (Gainesville, USA, dataset).

Crop	CO_2 (ppm)	Precipitation (%)	Temperature (^oC)							
			+1.5	+2	+2.5	+3	+3.5	+4	+4.5	+5
Corn and Soybean	400, 470, 540, 610, and 680	-20								
		-15								
		-10								
		-5								
		+5								
		+10								
		+15								
		+20								

Table 3.3: Simulated temperature, precipitation, and CO_2 concentration ranges for wheat (Rothamsted, UK, dataset).

Crop	CO_2 (ppm)	Precipitation (%)	Temperature (^oC)				
Wheat			+0.5	+1.5	+2.5	+3.5	+4.5
	400, 540, and 680	-20					
		-10					
		10					
		20					

Observed climate, soil, and crop management practice data from Gainesville, USA was used for corn and soybean, and Rothamsted, UK was used for wheat. Corn and wheat grains are the most common feedstocks used today for bioethanol, and soybeans for biodiesel. Agricultural residues such as corn stover, wheat straw, and soybeans stalks also have the potential for being used as biofuel feedstocks [15]. Besides data availability, one of the criteria of selecting suitable study sites was their representativeness for the crops.

The baseline climate data were modified as follows:

- Corn and soybean: for daily and maximum temperature changes, the baseline data were altered by +1.5, +2.0, +2.5, +3.0, +3.5, +4.0, +4.5, and +5.0 ^oC, and for precipitation changes of ±5, ±10, ±15, and ±20% of the baseline. The baseline CO_2 concentration of 330 ppm was altered by +70, +140, +210, +280, and +350 ppm. The ranges were based on the summary projections by the IPPC in its AR4 [50].
- Wheat: daily minimum and maximum temperature were altered by +0.5, +1.5, +2.5, +3.5, and +4.5 ^oC, and ±10 and ±20% for precipitation. Baseline CO_2 concentration was altered by +70, +210, and +350 ppm. The ranges were based on the summary projections based on the IPCC AR5 report [34].

3.2.3 Soil data

Soil characteristics play a very important role in the crops ability to extract water and nutrients for its growth. The soil must provide a satisfactory environment for crops growth if crops are to grow to their potential.

The generic deep sandy loam (SALO) soil [198] and sandy clay loam (SCL) soil [210] provided with the DSSAT-CSM model were used for Gainesville, USA, and Rothamsted, UK, respectively The data includes soil physical properties (soil texture, soil bulk density and soil water retention characteristics) and soil chemistry (soil organic matter, mineral nitrogen, and pH.). Tables 3.4 and 3.5 show the profile of the soils used in the study. The soils were chosen to test the models sensitivity to future climate change under growth conditions that are only limited by weather variables (such as air temperature, solar radiation, precipitation, and atmospheric CO_2).

Table 3.4: Summary of the soil characteristics for the SALO soil, Gainesville, USA [198].

Table 3.5: Summary of the soil characteristics for the SCL soil, Rothamsted, UK [210].

3.2.4 Crop management data

Simulations were run for the three major crops widely grown for energy purposes – corn, soybean, and wheat for the cultivars McCurdy 84aa, PIO332, and Maris Funden, respectively. Because crop yield varied not only due to variability in weather, but also soil properties, cultivar and management practices, the most common optimal yield conditions, and a high yielding cultivar for each crop were carefully selected and fixed throughout the study. Crop cultivars were selected by conducting several experiments using different crop cultivars and the high yielding cultivars were chosen for each crop.

Simulations were run under rain fed conditions to examine the effect of climate change scenarios on the energy crops yield. Irrigated condition was not considered because studies by [16, 41, 196] showed that the energy balance of maize ethanol showed that the energy balance of maize ethanol in the Southeastern USA varied much more across years under rainfed conditions than irrigated conditions as a result of weather and climate variability. The crop management data includes planting date, plant population (per ha), row spacing, planting depth, planting method, fertilization, and herbicides application. A common management data were adopted for each crop for all simulations. Simulated plants populations (plants m^{-2}) for the respective crops were: corn - 7.2, soybean - 22, and wheat - 277. Planting depth (cm) was 7, 3, and 4 for corn, soybean and wheat, respectively. Simulated raw spacing (cm) for the respective crops was: corn – 61, soybean – 76, and wheat – 17.

Energy crop biomass production typically requires fertilizers, since Nitrogen (N) and Phosphorus (P) are often the major limiting nutrients in agricultural soils. N mass fraction in plants ranges between 1% and 6% and is absorbed as nitrate or ammonium, while P mass fraction in plants is 0.1–0.5% or up to 1.0% and is generally absorbed as dihydrogen phosphate or monohydrogen phosphate depending on soil pH [211]. Thus, simulations were also run under nutrients limiting conditions. N, K, and P mineral fertilizers were simulated to ensure that the soil contains sufficient supply of growth nutrients and also to supplement nutrients loss due to crop residue removal from the field [79, 139]. In the DSSAT-CSM model, fertilizer materials (N, P, K) are applied differently in the application pull-down menu. N, K, and P were simulated in the form of urea/ammonium nitrate, potassium sulphate, and single superphosphate, respectively. High N treatment was simulated for corn and wheat, soil mineral N was set to 180 kg ha^{-1} each, and 130 kg ha^{-1} for soybean [212-214].

3.2.5 Validation of the models

A number of studies involving the evaluation of climate change impact on crop productivity have been conducted for CERES-Maize (e.g. [26, 215-219]), CERES-Wheat (e.g. [220-225]), and CROPGRO-Soybean (e.g. [226-232]). However, to ensure the accuracy of the model predictions, the average simulated grain and biomass yields were compared with observed yield data. The summary of the models validation is given in Table 3.6.

Table 3.6: Observed and simulated average grain and biomass yields [233, 16, 187].

Crop	**Grain yield (kg ha^{-1})**		**Biomass yield (kg ha^{-1})**	
	Simulated	**Observed**	**Simulated**	**Observed**
Corn	12984	11525	11404	22171
Soybean	3927	2700	2330	22400
Wheat	5955	7700	5895	5408

3.3 GHG emissions calculation

3.3.1 LCA model

GHG emissions from the crop yields under baseline and climate change scenarios as explained in section 3.2.2 were calculated for first generation biofuels: bioethanol and biodiesel, and second generation biofuels: biomethanol and bioelectricity using a life cycle assessment (LCA) approach in accordance with the ISO 14044 standard [128]. The LCA methodology employed in the study advocates the system boundary expansion method –

"displacement method" or "substitution method" for LCA [72, 234]. The LCA steps are described in subsequent sections.

Models were developed using GaBi v4.4 software [235]. GaBi v4.4 is a powerful modeling, reporting & diagnostic software tool for LCA developed by the PE INTERNATIONAL [236] with about 5570 LCI (Lifecycle Inventory) datasets. It is the most trusted product sustainability solution for LCA with over 10,000 users [236]. GaBi models every element of a product or system from a life-cycle perspective. It also provides an easily accessible and constantly refreshed content database that details the costs, energy and environmental impact of sourcing and refining every raw material or processed component of a manufactured item.

The crop yields were based on simulated model outputs from the DSSAT-CSM model and were used as inputs for the LCA models. In this study, average energy crop yields over 10 years were taken to smooth out annual variations due to temperature and precipitation differences. Baseline and climate change scenarios were created in the GaBi v4.4 software from the resulting simulated crop grain/seed and stover/stalk yields using *'if'* function formula as shown in Figure 3.3.

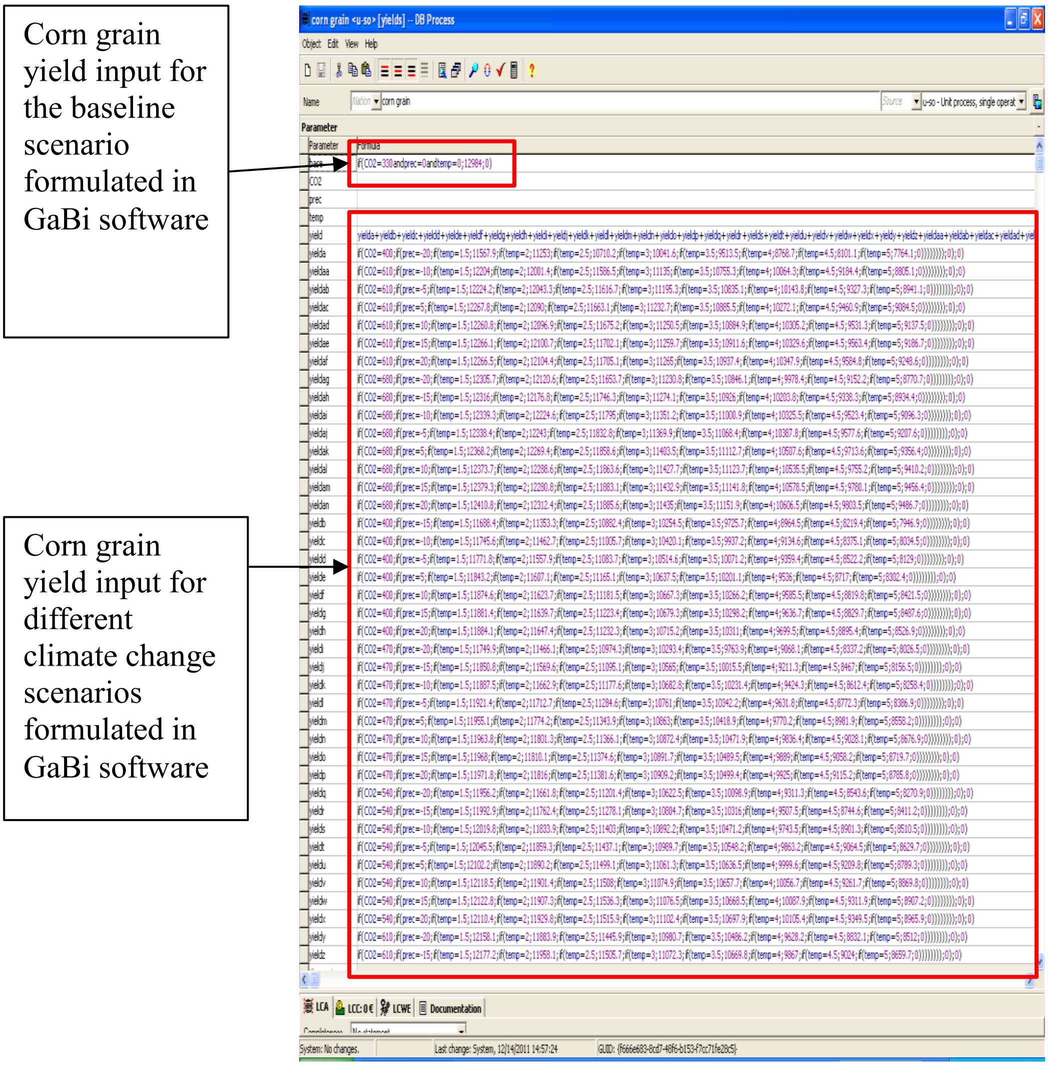

Figure 3.3: Screen shot showing an example of corn grain yields inputs in GaBi model as a function of climate scenario.

3.3.2 System boundaries

The system boundary in this study as shown in Figures 3.4-3.6 included energy crop (feedstock) production and transportation, biofuels processing, and biofuels distribution to service station or national grid (where applicable). The importance of including land-use change emissions in the GHG balance of biofuels was highlighted by [100] and [177]. Direct land use (transformation from non-arable to arable land for biofuels production purposes) was included in the analysis and crop farming activities such as planting, seeds, application of herbicides, harvesting, and fertilizers were also included. Upstream activities such as manufacturing of equipment/machines and chemicals were taken into account. The average 100 km feedstock transportation data was considered in the study [142]. Waste heat produced in the biofuel processing stage was not considered throughout this thesis since energy recovery from waste was not within the scope of the study.

3.3.2.1 First-generation biofuels – (Aim 2)

As explained in the previous chapter, CERES-Maize (corn), CERES-Wheat (wheat) and CROPGRO-Soybeans (soybeans) simulation grain yields data were used as input for biofuels production. Production of corn bioethanol (CBE) was compared to conventional gasoline [4, 150] and soybean biodiesel (SBD) was also compared with conventional petroleum diesel [237]. The life cycle GHG emissions savings of gasoline and biodiesel as substitutes for fossil gasoline and diesel respectively were calculated based on their respective models. A fuel substitution ratio (see equation 3.8) of 0.62033 was calculated for bioethanol and 0.88069 for biodiesel. In terms of co-products allocation, DDGS formed as a co-product during the bioethanol production process replaces corn meal using a substitution ratio of 1 based on the protein content of the by-products and their relevance as food components [96, 157]. Soybean meal produced as a by-product of biodiesel production was considered as a substitute for rape meal, the glycerine produced from esterification plants was considered as a substitute for conventional glycerine in equal parts - substitution ratio of 1 [238, 239]. The system boundary for first-generation technologies is given in Figure 3.4.

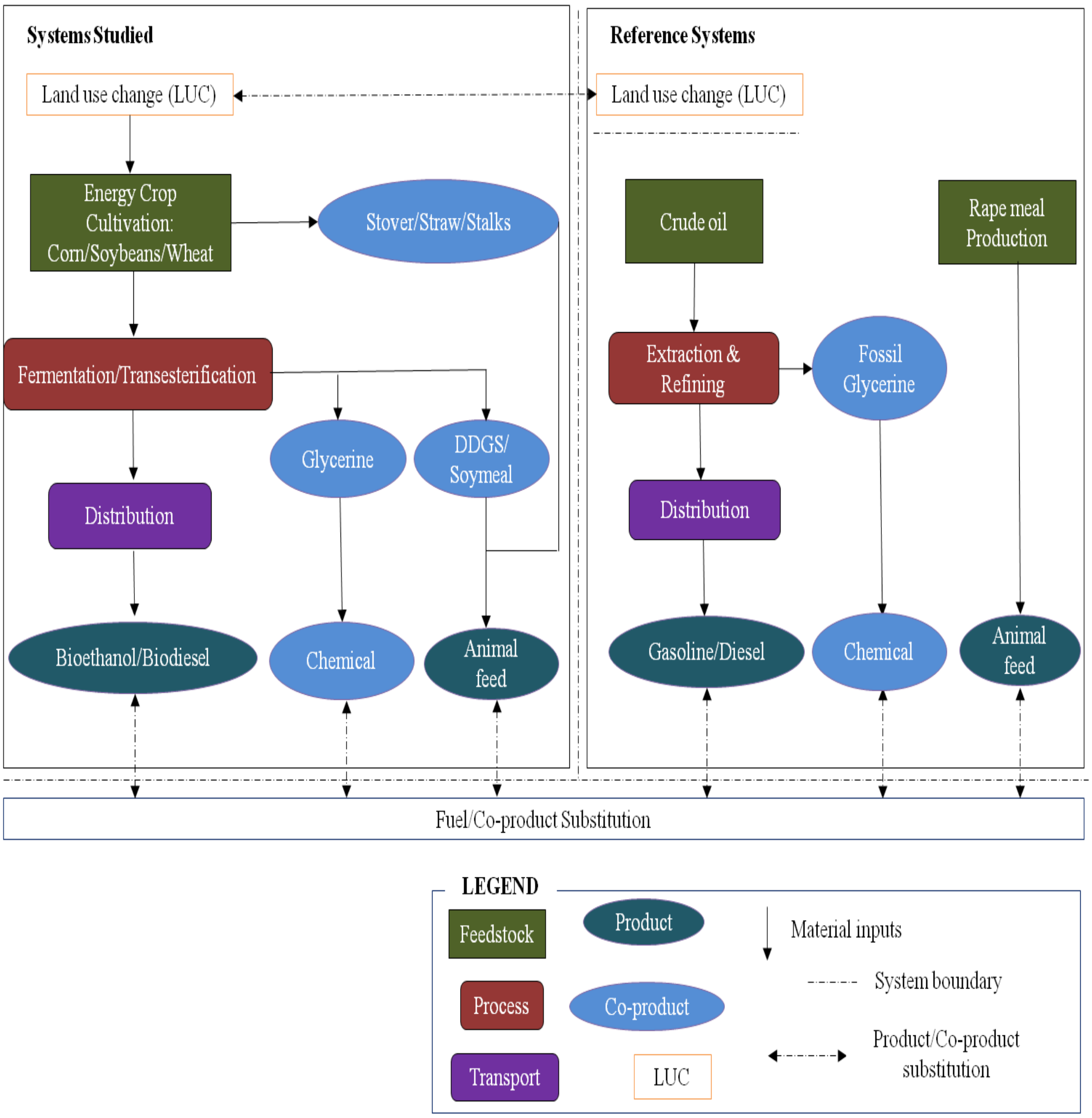

Figure 3.4: System boundaries of first-generation technologies (CBE, WBE & SBD).

3.2.2.2 Second-generation biofuels – (Aim 3)

For second-generation biofuels, whole crop utilization (both grain and by-products) was considered in the study. This involves combined production of both first-generation biofuels from grain and second-generation biofuels from by-products: corn stover from corn, wheat straw from wheat, and soybeans stalks from soybeans.

For corn integrated biomethanol (CIBM) production, corn grains yield was assumed to be used for the production bioethanol (as discussed in 3.3.2.1) and corn stover yield, which is the by-product of corn was assumed to be used for biomethanol production through biomass gasification and biomethanol synthesis process. For wheat integrated biomethanol production (WIBM), wheat grains yield was considered to be for bioethanol production (as previously described) and wheat straw, a by-product of wheat was assumed to be used for biomethanol production. Similarly, soybeans seeds yield was used for biodiesel production and the stalks yield was assumed to be channeled into biomethanol production for soybeans integrated biomethanol (SIBM) production. Figure 3.5 shows the system for biomethanol production.

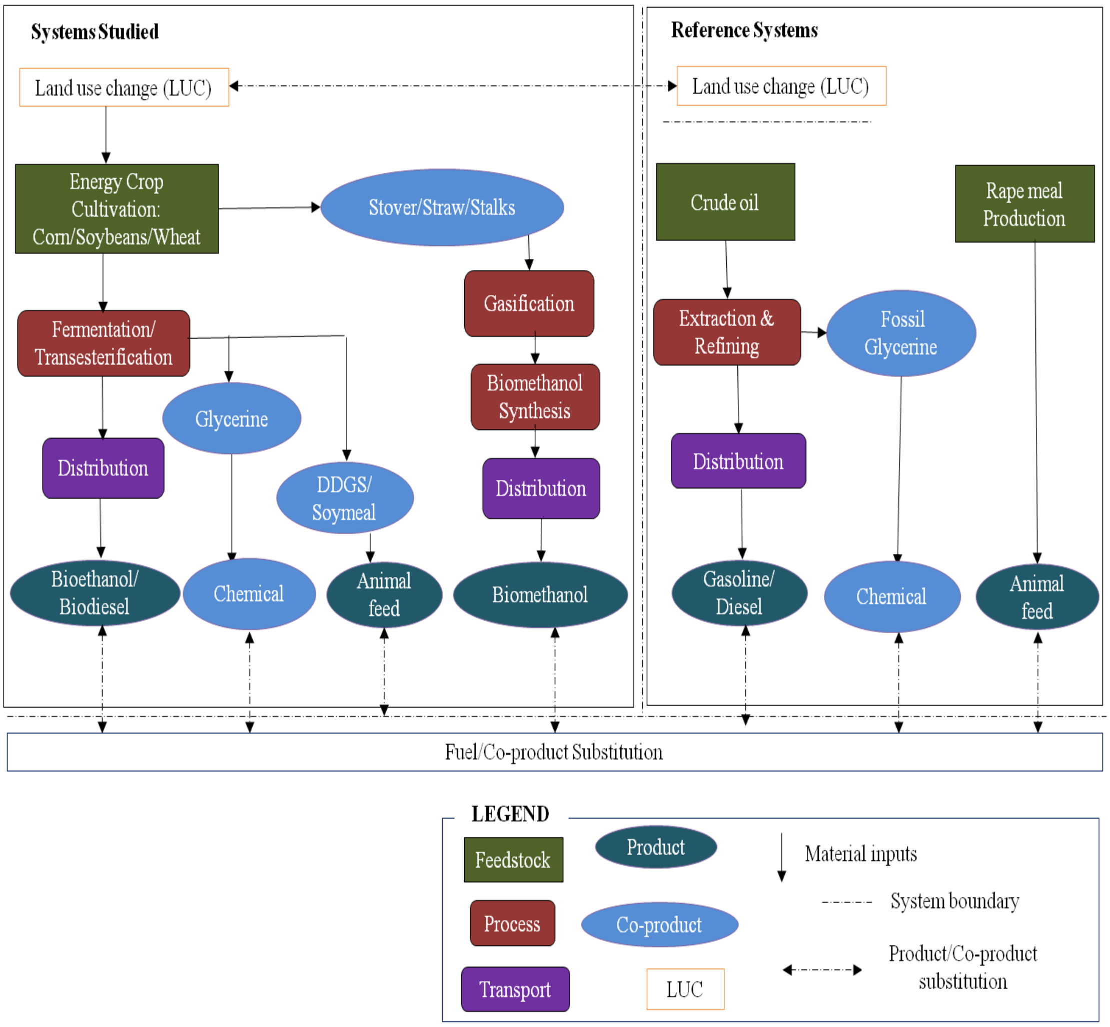

Figure 3.5: System boundary for integrated biomethanol production process.

Three technologies were also considered for bioelectricity production: corn integrated bioelectricity (CIBE), soybean integrated bioelectricity (SIBE), and wheat integrated bioelectricity (WIBE). For CIBE production, corn grain yield was utilized for the production bioethanol (as discussed in 3.3.2.1) and corn stover yield (by-product of corn) was utilized for bioelectricity production through a BIGCC process. For SIBE, soybean seeds yield was utilized for biodiesel production and the stalks yield was utilized for bioelectricity production through a BIGCC process. For WIBE, wheat grains yield was utilized for bioethanol production (as previously described), and wheat straw, a by-product of wheat was utilized be used for bioelectricity production through a BIGCC process. The system boundary for bioelectricity production is given in Figure 3.6.

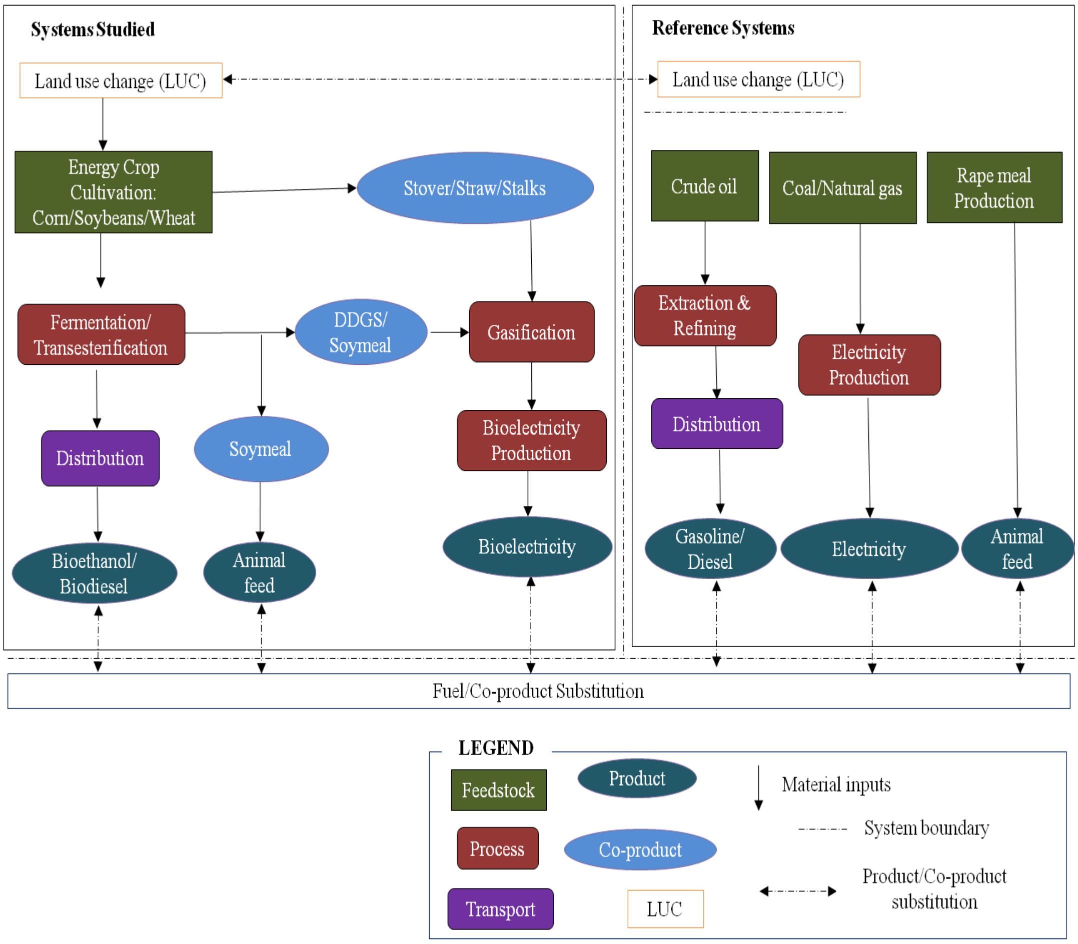

Figure 3.6: System boundary for integrated bioelectricity production process

3.3.3 Functional unit

The functional unit is defined as a hectare (ha). All impact assessments are of biofuels from energy crop feedstock produced per ha of land (net GHG emissions savings expressed in kg CO_2-eq. per ha per annum).

3.3.4 Key assumptions

Many LCA studies ignored the environmental impact of residue removal for bionergy production [144]. It has been recognized that residues removal for bioenergy production purposes may have strong environmental influence on many factors such as N_2O emission from soil, nitrate leaching and changes in soil carbon pools [79, 139]. Residue removal from from the field may lead to nutrients loss from soil , which must be added to replenish the soil for successful subsequent crop production. It was assumed that 80% of the residues (corn stover/soybean stalks/wheat straw) from agricultural cultivation are collected in round bales and converted to biofuels and the rest are left (incorporated) on the field to maintain soil organic carbon (SOC) and soil fertility [71, 137]. Land use change (land transformation from non-agricultural to arable land) was also considered to account for the depletion of soil carbon pools and additional GHG emissions, which occurs when non-agricultural land is transformed to arable land for biofuel purposes.

3.3.5 Reference system

The biofuels produced were compared to their respective fossil counterparts [5]. Co-products from the biofuels pathway also replace existing animal feeds and chemicals (where applicable). The LCA of petroleum-based fossil fuels – gasoline and diesel included extraction of crude oil, transportation to the refinery, refining, and distribution to service station (point of use).

3.3.6 Life cycle inventory (LCI)

LCA models for the biofuel technologies considered were constructed using LCI data from ecoinvent v2.0 database [199]. An example of the model for biodiesel from soybeans is shown in Figure 3.7. 'US' (LCI data based on production technologies in the USA) and

‘RER’ (LCI data based on production technologies in Europe) LCI datasets were preferentially selected in the study. However, limited availability of data has always been one of the critical issues in LCA studies, where data were not available, ‘CH’ LCI (inventory data based on production technologies from Switzerland).

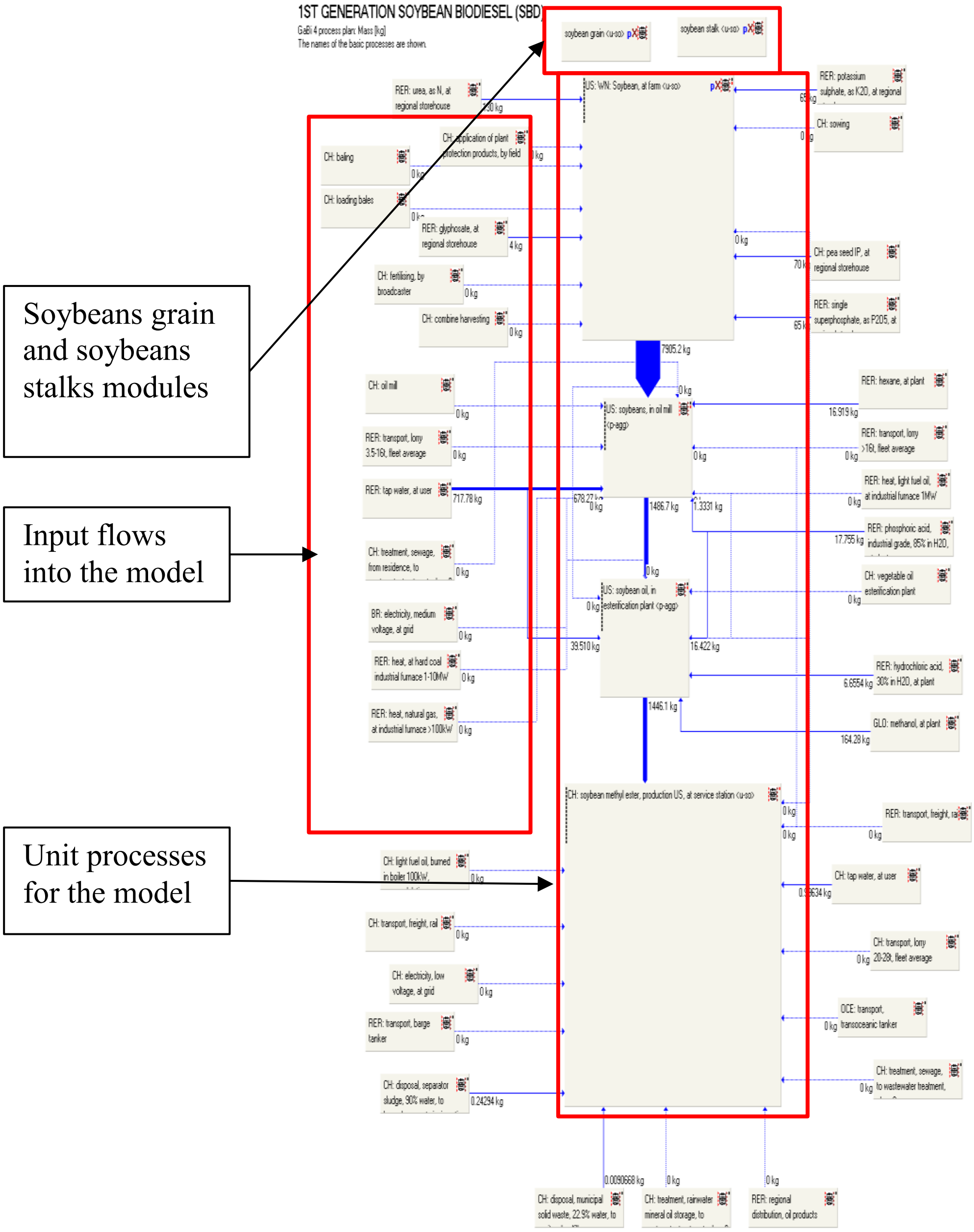

Figure 3.7: Screen shot showing an example of life cycle model for biodiesel production showing the entire unit processes and the input flows for each unit process.

3.3.6.1 Input/output data

Data output from the crop system model and LCI data from the ecoinvent database were used in the compilation. The life cycle of the biofuels was divided into:

- Crop production and management data (materials and energy inputs during farm operations), data output (crop yields/ha) from the DSSAT-CSM model, and all transportation involved in the process.
- Biofuel conversion at the plant, which includes material processing techniques (energy and materials used in converting crops into energy products - biofuels), and transportation.
- Biofuel distribution to the users at the service station.

Output data is the calculated life cycle impact assessment (LCIA) of the processes.

3.3.7 Life cycle impact assessment (LCIA)

The cumulative LCIA results from ecoinvent for GHG warming potential were taken by applying the CML2001, 100 years GWP methodology [240] due to its relevance to current legislative goals for climate change mitigation [50]. An example of model calculation using the CML2001, GWP is shown in Figure 3.8. The calculation of lifecycle GHG emissions includes carbon dioxide (CO_2) of fossil origin and soil carbon, methane (CH_4) and nitrous oxide (N_2O) based on their relative contribution to global warming (GW).

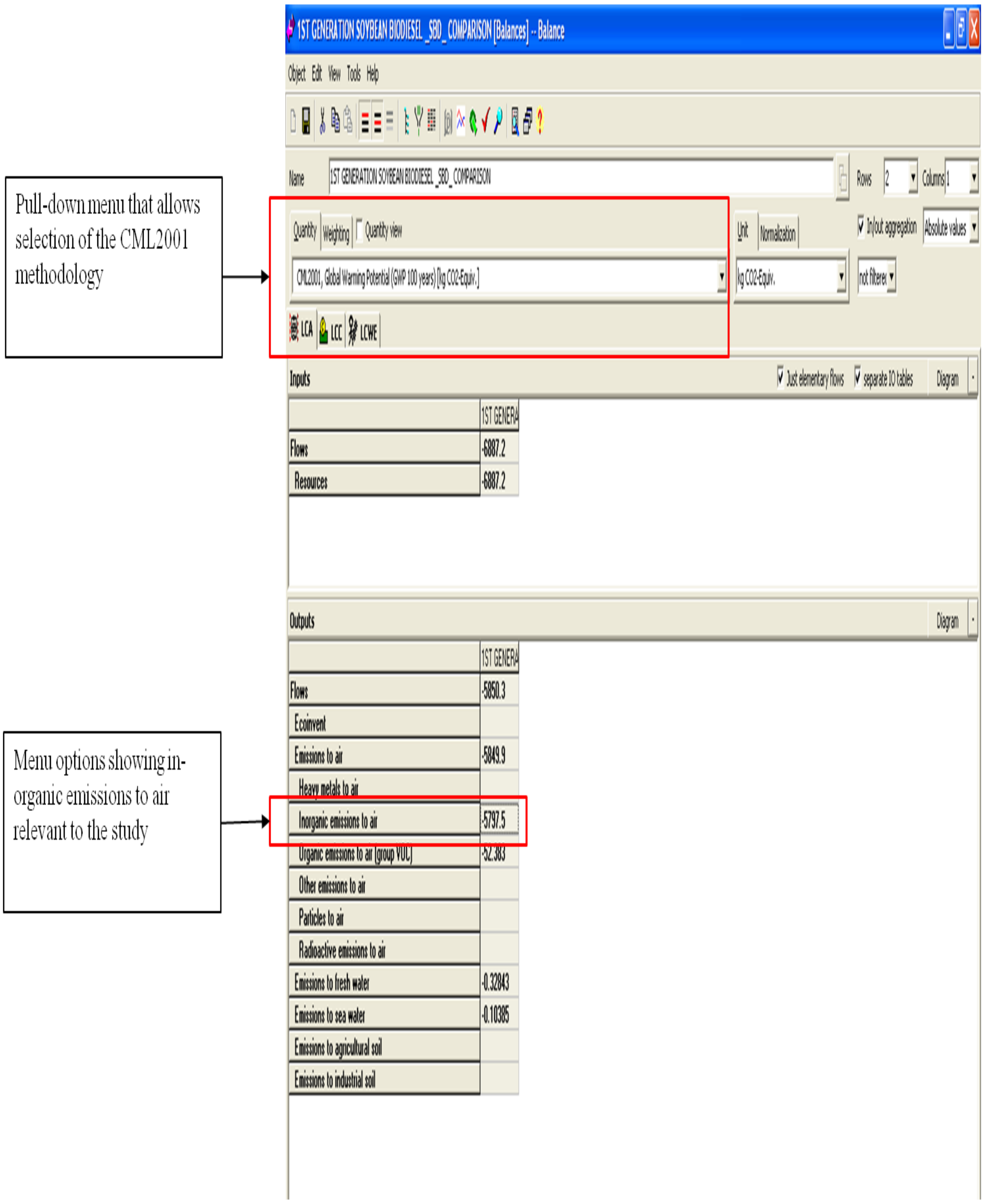

Figure 3.8: Screen shot showing the window for selecting the LCA calculation methodology.

These GHG emissions were aggregated to give a single figure for emissions, which is expressed in expressed as kg CO_2-equiv. ha^{-1} yr^{-1}. The analysis accounts for the GHG emissions from energy crop cultivation (farm operations), biofuel conversion processes, and distribution to regional storage (equation 3.1).

$$GHG_{biofuels} = GHG_{farm} + GHG_{process} + GHG_{distrib.} \tag{3.1}$$

3.3.7.1 Crop cultivation

Total GHG emissions associated with cultivation of energy crops were calculated as the sum of GHG emissions from changes in soil carbon due to land use change (transformation to arable land), farm machinery, herbicides, feedstocks (grain/straw) collection from field, loading, transportation, and transport of farm fertilizers and seeds. Using the farming input data described in Tables 3.7, 3.8, and 3.9, the model calculates the GHG emissions from corn, soybeans and wheat cultivation, respectively for no-till system (equation 3.2). This data was obtained from the ecoinvent database, the University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) extension services and simulated (experimental) data from the DSSAT-CSM models. The fertilization data for each of the crops considered was carefully selected since crop yields are affected by the rate of fertilizer application. The effect was first determined on whole crop yield (grain/seeds and residues) by simulating crop yields using variable fertilization rates. The optimum fertilization rate with the highest output (grains/seeds plus residue yield) were chosen and applied in this study for crop yield simulation.

$$\begin{aligned} GHG_{farm} &= GHG_{seed} + GHG_{N-fert} + GHG_{P-fert} + GHG_{K-fert} + GHG_{herb} \\ &+ GHG_{transport} + GHG_{fossils} + GHG_{preoperation} + GHG_{equipments} \end{aligned} \tag{3.2}$$

Where, GHG_{seed}, are the emissions involved in seed production and transport, $GHG_{N\text{-}fert}$, $GHG_{P\text{-}fert}$, and $GHG_{K\text{-}fert}$, are the emissions involved in the production and transport of nitrogen, phosphate, and potassium fertilizers respectively. GHG_{herb}, are the emissions involved in the production and transport of herbicides, GHG_{fossil}, are the emissions from fossil fuel use during farm operations such as sowing, balling, fertilizers and herbicides application, and harvesting, $GHG_{transport}$, are the total emissions involved during biomass transportation from farm to the processing plant, $GHG_{preoperations}$, are the emissions from soil during land transformation, and $GHG_{equipment}$ are emissions from manufacture of farm machinery.

Table 3.7: Inventory data for the cultivation of 1 ha of corn [199, 214, 213]. Grain and stover yields output depend on climate scenario

Inputs	**Amount**	**Unit**
US: application of plant protection products, by field sprayer [work processes]	10000	sqm
US: baling [work processes]	stover yield	pcs.
US: combine harvesting [work processes]	10000	sqm
US: fertilising, by broadcaster [work processes]	30000	sqm
US: loading bales [work processes]	quantity of bales	pcs.
US: maize seed IP, at regional storehouse [seed]	20	kg
US: sowing [work processes]	10000	sqm
US: atrazine, at regional storehouse [Pesticide]	3	kg
US: potassium sulphate, as K_2O, at regional storehouse [mineral fertiliser]	90	kg
US: single superphosphate, as P_2O_5, at regional storehouse [mineral fertiliser]	90	kg
US: transport, lorry >16t, fleet average [Street]	quantity of bales	tkm
US: urea, as N, at regional storehouse [organics]	180	kg
CH: transformation, to arable, non-irrigated [ecoinvent]	10000	sqm
Outputs		
US: corn stover, at farm [plant production]		kg
US: corn grain, at farm [plant production]		kg

Table 3.8: Inventory data for the cultivation of 1 ha of soybeans [199, 241]. It is important to note that seed and stalk yields output depend on climate scenario.

Inputs	**Amount**	**Unit**
US: application of plant protection products, by field sprayer [work processes]	10000	sqm
US: baling [work processes]	stalks yield	pcs.
US: combine harvesting [work processes]	10000	sqm
CH: fertilising, by broadcaster [work processes]	20000	sqm
CH: loading bales [work processes]	quantity of bales	pcs.
US: soybeans, at regional storehouse [seed]	70	kg
US: sowing [work processes]	10000	sqm
US: glyphosate, at regional storehouse [Pesticide]	4	kg
US: potassium sulphate, as K_2O, at regional storehouse [mineral fertiliser]	65	kg
US: single superphosphate, as P_2O_5, at regional storehouse [mineral fertiliser]	65	kg
US: transport, lorry >16t, fleet average [Street]	quantity of bales	tkm
US: urea, as N, at regional storehouse [organics]	130	kg
Transformation, to arable, non-irrigated [ecoinvent]	10000	sqm
Outputs		
US: soybean, stalk [fuels]		kg
US: soybean, at farm [plant production]		kg

Table 3.9: Inventory data for the cultivation of 1 ha of wheat [199]. It is important to note that grain and straw yields output depend on climate scenario.

Inputs	Amount	Unit
CH: application of plant protection products, by field sprayer [work processes]	10000	sqm
CH: baling [work processes]	straw yield	pcs.
CH: combine harvesting [work processes]	10000	sqm
CH: fertilising, by broadcaster [work processes]	30000	sqm
CH: loading bales [work processes]	quantity of bales	pcs.
CH: sowing [work processes]	10000	sqm
CH: wheat seed IP, at regional storehouse [seed]	100	kg
RER: 2,4-D, at regional storehouse [Pesticide]	1.1	kg
RER: potassium sulphate, as K_2O, at regional storehouse [mineral fertiliser]	65	kg
RER: single superphosphate, as P_2O_5, at regional storehouse [mineral fertiliser]	65	kg
RER: transport, lorry >16t, fleet average [Street]	quantity of bales	tkm
RER: urea, as N, at regional storehouse [organics]	180	kg
Transformation, to arable, non-irrigated [ecoinvent]	10000	sqm
Outputs		
CH: wheat grains, at farm [plant production]		kg
CH: wheat straw, at farm [plant production]		kg

3.3.7.2 Biofuel processing

GHG emissions associated with the production of biofuel were calculated using data from the ecoinvent database (equation 3.3).

$$GHG_{process} = GHG_{pre-treatment} + GHG_{Chem/enz} + GHG_{water} + GHG_{electricity} + GHG_{facilities} + GHG_{treatment} \quad (3.3)$$

Where $GHG_{pre\text{-}treatment}$, are the emissions involved during biomass pre-treatment such as drying, and milling, $GHG_{chem/enz}$ are the emissions during the production and transport of the chemicals and/or enzymes used in the conversion process, GHG_{water} are the emissions involved in the production and supply of tap water used in the processing plant, $GHG_{electricity}$ are the emissions during the production of electricity used in the biofuel processing,

$GHG_{facilities}$ are the emissions involved in the construction of the biofuel processing plant, and $GHG_{treatment}$ are the emissions during wastewater treatment from the production process. Process modules data inventories for the biofuels considered are described in the following subsections.

3.3.7.2.1 First generation corn bioethanol (CBE) and wheat bioethanol (WBE)

This was undertaken to evaluate the net life cycle GHG emissions associated with bioethanol production from corn and wheat grain as potential replacement for energetically equivalent petrol (gasoline) from fossil crude oil. The resulting flow charts for CBE model from corn and WBE model wheat grain are illustrated in Appendices J and K respectively. The flow charts were delineated into separate sub-processes, mainly to assist with process chain specifications and subsequent LCI data requirement.

3.3.7.2.1.1 Grains in distillery

LCI data as shown in Tables 3.10 and 3.11 refers to the data inputs for the production of hydrated bioethanol 95% (d.b), and dried distiller grains with soluble (DDGS) (wet basis) from 1 kg of grains as obtained from the ecoinvent database. The multi-output process delivers the product and co-product 'bioethanol, 95% in H_2O', and 'DDGS', respectively. The process described corresponds to the dry-milling grains-to-bioethanol technology including all necessary transport of the grain to the processing plant (assumed 100 km radius).

Table 3.10: LCI input data for corn grains, in distillery, referred to the production of bioethanol (95% in H_2O) from 1 kg corn grain [199].

Table 3.11: LCI data for wheat grains, in distillery, referred to the production of bioethanol (95% in H_2O) from 1 kg wheat grain [199].

3.3.7.2.1.2 Bioethanol, 99.7% in H_2O, from grains, at distillation

LCI data presented in Table 3.12 refers to the production of 1 kg bioethanol (99.7% in H_2O) through distillation process.

Table 3.12: LCI data for the distillation of bioethanol (95% in water) to bioethanol (99.7% in H_2O) [199].

3.3.7.2.2 First generation soybean biodiesel (SBD)

This option was undertaken to evaluate the net life cycle GHG emissions associated with biodiesel production from soybean seed as a potential replacement for energetically equivalent fossil diesel from crude oil. The resulting flow charts for SBD model from soybean is illustrated in Appendix L.

3.3.7.2.2.1 Soybeans, in oil mill

LCI data as shown in Table 3.13 refers to the production of soybean oil and soybean meal from 1 kg soybean grains. The multi-output process delivers the product and co-product soybean and soybean meal, respectively. The process describes a typical oil mill designed for soybean oil solvent extraction (including pre-cracking of soybeans, dehulling, oil extraction, meal processing, and oil purification), within the US context.

Table 3.13: LCI data for soybean seeds, in oil mill process, referred to the conversion of 1 kg soybean seeds to oil and meal [199].

3.3.7.2.2.2 Soybeans oil, in transesterification plant

LCI dataset as depicted in Table 3.14 refers to the production of soybean methyl ester (biodiesel), and glycerin, from 1 kg soybean oil. The multi-output production process delivers soybean methyl ester (biodiesel) as main product and glycerine as co-product. The process described a typical vegetable oil esterification plant designed for the production of methyl ester (biodiesel).

Table 3.14: LCI data for soybean oil, in esterification plants, referred to 1 kg soybean oil [199].

3.3.6.3 Second generation biofuels

3.3.6.3.1 Biomass Integrated Gasification and Biomethanol synthesis (BIGBMS)

These models for combined production of corn grain bioethanol from grain and biomethanol from stover/DDGS, CIBM, wheat grain bioethanol from grain and biomethanol from straw/DDGS, WIBM, and soybean seed biodiesel and biomethanol from stalk/glycerine, SIBM are illustrated in Appendices M, N, and O respectively.

LCI dataset in Table 3.15 refers to the full-methanol steam reforming of syngas derived from biomass gasification (subsequent processing of the syngas is considered). The process describes the production of biomethanol derived from syngas through integrated biomass gasification and biomethanol synthesis system (Figure 3.6). Biomass gasification was carried out at 900^{o}C and the technology corresponds to an average indirectly heated, atmospheric, circulating fluidized bed gasification, followed by a low temperature wet gas treatment. The gasifier was first modeled using an Excel application and later transferred to GaBi LCA software for LCA analyses based on process technology reported in [242]. The gasification model predicts the mass, composition, higher heating value, and the energy content of syngas produced per 1 kg of the dry biomass – corn stover, wheat straw, soybeans stalks, DDGS from corn and wheat bioethanol, glycerine from soybeans biodiesel, (see Table 3.16). The composition (% wt) of the resulting syngas at the outlet of the gasifier is detailed in Table 3.17. Comparison of the calculated syngas compositions with published data from [242-244] validated this model. Biomethanol yield from the resulting syngas was simulated using CAPE-OPEN to CAPE-OPEN (COCO) simulation environment software [245], which is based on the process model described in [246] and validated by data from the ecoinvent database [212, 240].

Table 3.15: LCI flows for integrated biomass gasification and biomethanol synthesis, at plant, referred to 1 kg of biomass residue - Corn Integrated Biomethanol (CIBM), Wheat Integrated Biomethanol (WIBM) and Soybean Integrated Biomethanol (SIBM) synthesis [199]. Biomethanol output depends on syngas yield from gasification, which also depend on feedstock material.

Table 3.16: Composition of the crop residues and co-products used as inputs into the gasification model (% dry ash-free basis) [247-249].

	Corn stover	**DDGS**	**Soybeans stalks**	**Glycerine**	**Wheat straw**
C	51.89	44.93	47.7	58.05	43.2
H	5.45	7.26	6.6	10.58	5
O	41.48	36.45	47.0	29.82	39.4
N	0.84	5.31	0.6	0.19	0.4
S	0.34	1.04	0.10	0.01	0.2
Moisture (%)	10.4	-	-	-	10.5
Heating value (MJ/kg)	20.4	23.8	16.96	16.0	17.0
Ash (%)	8.1	5.8	6.08	1.19	5.6
Volatile matter (%)	77.4	82.6	68.95	-	75.3
Fixed carbon	-	-	15.62	-	-

Table 3.17: Gasification outputs result from the gasification models.

	Corn stover		**DDGS**		**Soybeans stalks**		**Glycerine**		**Wheat straw**	
Syngas yield (kg/kg)	2.857415		3.231709		3.049947		4.428656		3.335195	
Syngas composition (% wt)	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
CO	17.777	18.978	14.592	15.873	11.532	12.806	16.765	17.846	14.724	15.572
CO_2	21.928	23.409	19.147	20.827	22.607	25.105	13.593	14.469	21.647	22.894
CH_4	3.1069	3.3168	2.7691	3.0121	2.4452	2.7153	2.9539	3.1445	0.985	1.042
H_2	0.6709	0.7162	0.8042	0.8747	0.6637	0.7370	0.9773	1.0404	0.647	0.685
H_2O	6.3272	0	8.0677	0	9.9477	0	6.0587	0	5.450	0
N_2	50.189	53.579	54.619	59.4127	52.8029	58.6358	59.6516	63.4988	56.547	59.807
HHV (MJ/kg)	4.4737	4.7759	4.1540	4.5186	3.4655	3.8483	4.7223	5.0268	2.954	3.123

3.3.6.3.2 Biomass integrated gasification and combined cycle (BIGCC)

These models for combined production of corn grain bioethanol from grain and bioelectricity from stover/DDGS, CIBE, wheat grain bioethanol from grain and bioelectricity from straw/DDGS, WIBE, and soybean seed biodiesel and bioelectricity from stalk/glycerine, SIBE are illustrated in Appendices P, Q, and R respectively.

LCI data in Table 3.18 refers to the generation of bioelectricity from 1 kg corn stover, wheat straw, soybeans stalks, DDGS from corn and wheat bioethanol, and crude glycerine from soybeans biodiesel. The technology corresponds to typical BIGCC system (Figure 3.11). Dry biomass enters the gasification plant to obtain a synthesis gas (syngas), which after a cleaning process is sent to a gas turbine for complete combustion to generate electric power. The characteristics of the biomass feedstocks are given in Table 3.16. The gasifier and the syngas turbine plants were first modelled using an Excel application and later transferred to GaBi LCA Software for LCA analyses based on process technology reported by [242].

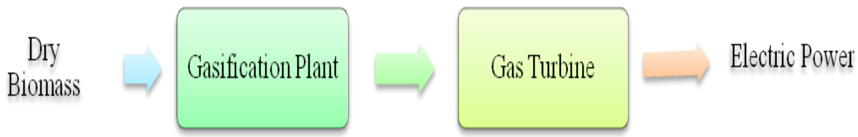

Figure 3.9: Schematic representation of the BIGCC plant

The gasification model predicts the mass, composition, higher heating value, and the energy content of syngas produced per 1 kg of the dry biomass, while the gas turbine model predicts the electric power output from the gas turbine from the resulting syngas (dry, nitrogen free). The composition (% wt) of the resulting syngas at the outlet of the gasifier is detailed in Table 3.17. Comparison of the calculated syngas compositions with published data from [242-244] validated this model. Cleaned (dry, nitrogen free) syngas is passed into a gas turbine engine where it is burnt to generate electricity. The syngas turbine model predicts the amount of electricity that can be produced from the resulting amount of syngas. Electric power output of the gas turbine was calculated using an electric power efficiency of 40% [250, 251]. The electric power output (n_{elec-p} *(MJ)*) was evaluated with reference to the high heating value (HHV) (MJ kg^{-1}) of dry syngas and is defined as:

$$n_{elec-p}(MJ) = \frac{(HHV_{PCO} + HHV_{PH2} + HHV_{PCH4})}{m_{syngas}} X\, 0.40 \qquad (3.4)$$

Where *PCO* is the percentage weight of CO in syngas, *PH2* is the percentage weight of H_2 in syngas, *PCH4* is the percentage weight of CH4 in syngas, and m_{syngas} is the total mass (kg) of syngas.

Table 3.18: LCI flows for integrated biomass gasification and combined cycle (bioelectricity production), at plant, referred to conversion of 1 kg biomass residue - corn stover/wheat straw/soybeans stalks [199]. Bioelectricity output depends on biomass feedstock.

Inputs	**Amount**	**Unit**
US: electricity, medium voltage, at grid	0.0958439	MJ
US: synthetic gas plant	9.3343E-10	pcs
US: tap water, at user	0.14326	kg
CH: transport, lorry 20-28t, fleet average	0.041306	tkm
CH: treatment, sewage, from residence, to wastewater treatment, class 2	6.0945E-5	m^3
CH: silica sand, at plant	0.012598	kg
CH: dolomite, at plant	0.010157	kg
RER: industrial furnace, natural gas	1.8939E-9	pcs
US: sodium hydroxide, 50% in H_2O, production mix, at plant	0.00082799	kg
US: sulphuric acid, liquid, at plant	0.0032898	kg
US: stover/straw/stalks, dry biomass	1	kg
US: zeolite, powder, at plant	0.0020803	kg
RER: disposal, inert waste, 5% water, to inert material landfill	0.022755	kg
RER: disposal, ash mixture, pure, 0% water, to municipal incineration	0.002238	kg
RER: disposal, ash mixture, pure, 0% water, to sanitary landfill	0.0016905	kg
RER: disposal, zeolite, 5% water, to inert material landfill	0.0020803	kg
Output		
US: electricity, medium voltage, at grid [supply mix]		MJ

3.3.6.4 Biofuel distribution

GHG emissions due to biofuel distribution were calculated equation 3.5.

$$GHG_{distribution} = GHG_{transport} + GHG_{treatment} + GHG_{disposal} + GHG_{electricity} + GHG_{reg-dist} \quad (3.5)$$

where, $GHG_{transport}$ are the emissions during biofuel transport from the plant to the service station, $GHG_{treatment}$ are emissions during wastewater treatment from the fuel service station, $GHG_{disposal}$ are the emissions involved in the disposal of municipal solid wastes from the fuel station to sanitary landfill, $GHG_{electricity}$ are the emissions during the production of electricity used in the station, and $GHG_{reg\text{-}dist}$ are emissions involved in the construction of service station. Data inventories for the distribution of the biofuels are described in the following subsections.

3.3.6.4.1 Bioethanol, 99.7% in H_2O, from grains, at service station

In Table 3.19, LCI data refers to the distribution of 1 kg of anhydrous bioethanol 99.7% in water from the processing plant to the fuel service station including all necessary transport (assumed 150 km by road).

Table 3.19: LCI data for the distribution of 1 kg anhydrous bioethanol, 99.7% in H_2O, from processing plant to the service station [199].

3.3.6.4.2 Soybean methyl ester (biodiesel), at service station

LCI data as shown in Table 3.20 refers to the distribution of 1 kg of soybean methyl ester (biodiesel) to the fuel service station including all necessary transport (assumed 150 km by road).

Table 3.20: Input flows for the distribution of 1 kg soybeans biodiesel to the service station [199].

3.3.6.4.3 Biomethanol, from biomass, at service station

LCI data as depicted in Table 3.21 refers to the distribution of 1 kg biomethanol from the processing plant to the fuel service station including all necessary transport (assumed 150 km by road).

Table 3.21: Input flows for the distribution of 1 kg biomethanol to the service station [199].

3.3.7 GHG emissions reduction due to fossil fuels replacement

The GHG emissions savings ($GHG_{savings}$) from the biofuel produced (e.g. Figure 3.10) was calculated as the difference between emissions from biofuel production ($GHG_{biofuel}$) (see equation 3.1) and emissions saved from fossil fuel replacement ($GHG_{f\text{-}saved}$) (see equation 3.7) plus emissions saved from co-products replacement ($GHG_{cp\text{-}saved}$). Calculations were made for both baseline and projected climate change scenarios (e.g. Figure 3.11).

$$GHG_{savings}(CF) = (GHG_{biofuel}) - (GHG_{f-saved} + GHG_{cp-saved}) \tag{3.6}$$

$$GHG_{f-saved} = GHG_{f-extraction} + GHG_{f-process} + GHG_{f-dist.} + GHG_{f-combust.} \tag{3.7}$$

Where, $GHG_{f\text{-}extraction}$, $GHG_{f\text{-}processt}$, $GHG_{f\text{-}dist.}$ and $GHG_{f\text{-}combust}$ are the fossil-derived GHG emissions from fossil fuel extraction, processing, distribution, and combustion of the displaced fossil fuel equivalent ($fossil_{equiv}$.) respectively. Combustion of the displaced fossil fuel is defined by the equation below.

$$GHG_{f-combust.} = \left(Carbon_{oxfactor} \; x \left(\frac{MW_{CO2}}{MW_{Carbon}} \right) x \;\; fossil_{equiv.} \right) \tag{3.8}$$

Where, $Carbon_{oxfactor}$ is the fossil carbon oxidation factor of 0.99 [49] used in calculating the carbon emissions from burning fossil fuels, MW_{CO2} is the molecular weight of CO_2, and MW_{Carbon} is the molecular weight of carbon in the displaced fossil-based fuel (fossil equivalent). The displaced fossil fuel equivalent ($fossil_{equiv.)},$ which is the amount (kg) of the replaced fossil reference system, is defined by the equation below.

$$fossil_{equiv.} = biofuel_{produced} \times S_r \tag{3.9}$$

Where, $biofuel_{produced}$, is the amount of biofuel produced per ha, and S_r is the substitution ratio between the biofuel and the conventional fossil fuel (equation 3.10).

$$S_r = \frac{CV_{biofuel}}{CV_{fossilfuel}} \qquad (3.10)$$

Where, $CV_{biofuel}$, is the calorific value of the biofuel produced in MJ/kg, and $CV_{fossilfuel}$, is the calorific value of the displaced fossil reference system also in MJ/kg.

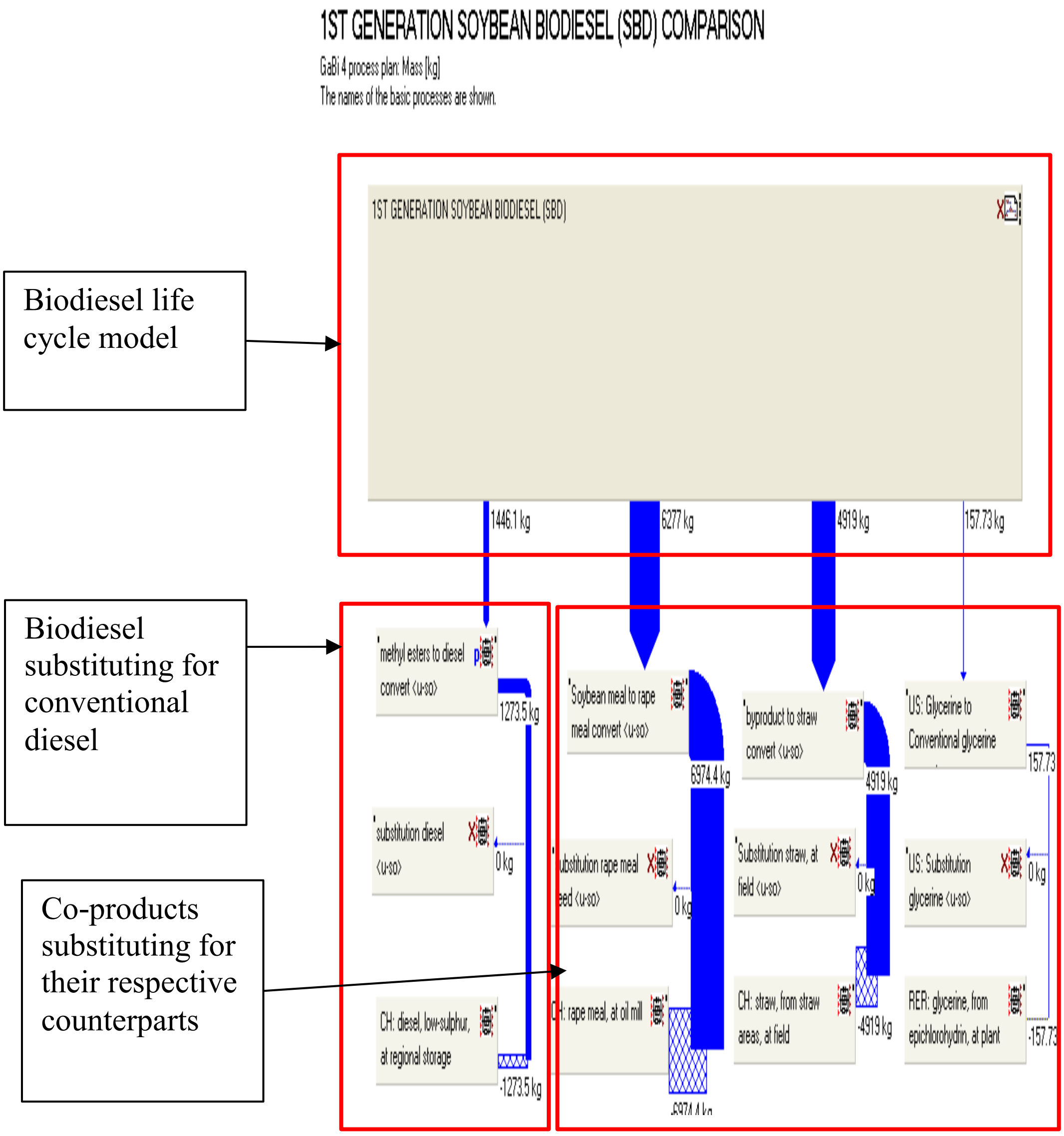

Figure 3.10: Print screen of SBD showing products substitution

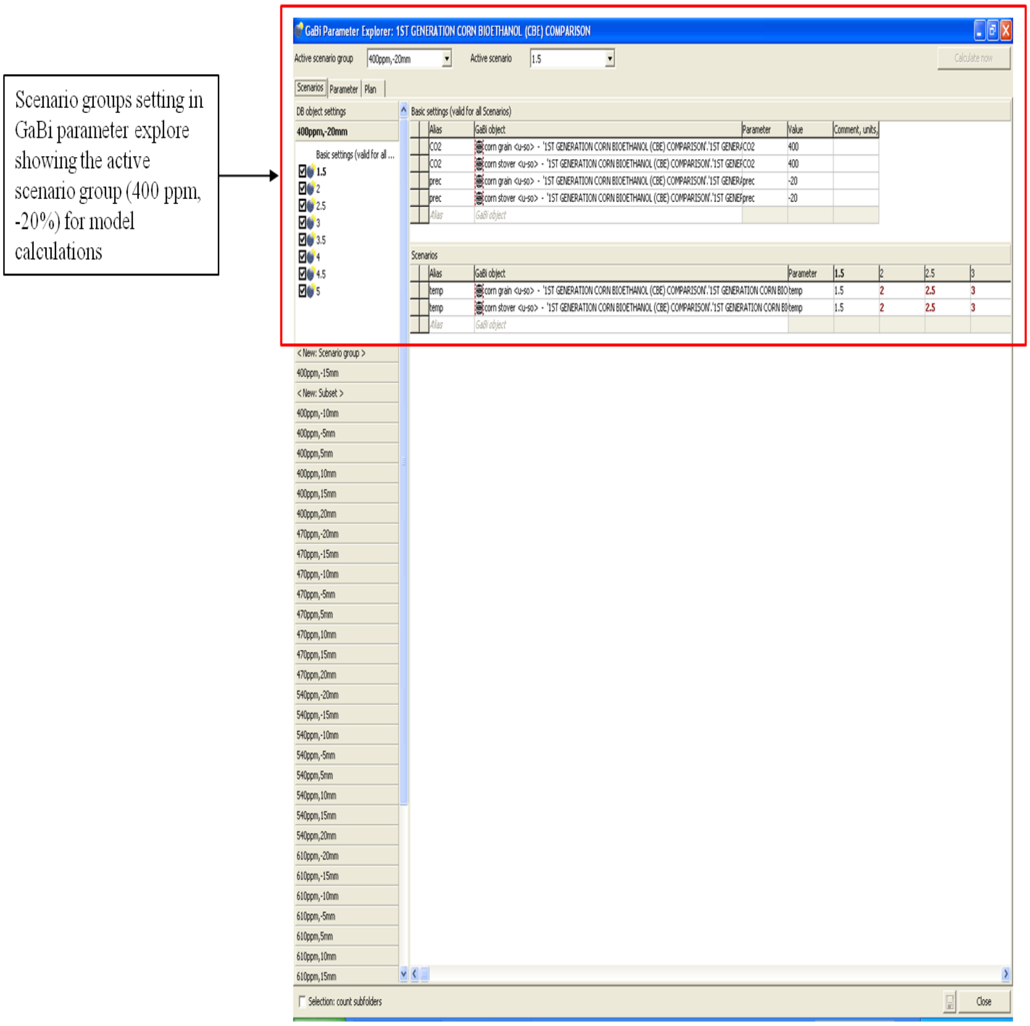

Figure 3.11: GaBi LCA calculations showing different climate change scenarios.

3.4 Summary

A number of studies that span several disciplines and methods have been conducted on the link between agriculture, climate, and yields of crops. This span from controlled field experiments; statistical analyses of past climates to integrated climate-crop models have been applied to understand the potential impacts of climate change on agriculture. These different approaches have different strengths and weaknesses. For instance, carrying field experiments to determine the crop's response to climate change is practically difficult, expensive, as well as time consuming. However, there are several attempts for utilizing CSM models that are easy to operate, and inexpensive. The models take into account various factors such as weather, soil, and crop management practices for specified regions. The DSSAT-CSM is one of the advanced packages widely being used today.

This chapter describes the novel approach applied for estimating the potential link between climate change, yields, and life cycle GHG emissions savings for common annual crops grown in the USA: corn and soybean. Corn and soybean are the most prevalent energy crops in the USA, and are the predominant source of feedstock for bioethanol and biodiesel production respectively. Wheat is the commonest crop grown in the UK, and like corn, is commonly used for bioethanol production. These crops were simulated using dataset for the location where they are grown in each country, and where there is availability of data in suitable format accepted by the CSM model.

CHAPTER 4: RESULTS

4.1 Introduction

This section presents the main empirical findings of the research. An analysis of the impact of climate change (combined effects of changing *T*, *P*, and $[CO_2]$) on potential average yields of corn, soybean, and wheat as feedstock for biofuel production is first presented. As earlier explained in the previous section (section 3), three climate variables were considered. These are (i) atmospheric air temperature, *T* (+1.5, +2, +2.5, +3, +3.5, +4, +4.5, and +5 ^{o}C – corn and soybean at Gainesville, USA) and (+0.5, +1.5, +2.5, +3.5, and +4.5 ^{o}C – for wheat at Rothamsted, UK) (ii) precipitation, *P* (+20, +15, +10, +5, -20, -15, -10, and -5% – for corn and soybean at Gainesville, USA) and (+20, +10, -20, and -10% - for wheat at Rothamsted, UK) (iii) atmospheric CO_2 concentration, $[CO_2]$ (400, 470, 540, 610, and 680 ppm – for corn and soybean at Gainesville, USA) and (400, 540, and 680 ppm – for wheat at Rothamsted, UK). Next, this section also presents the empirical results for the calculation of the potential life cycle GHG emissions of first-generation biofuels: CBE, WBE, and SBD, and second-generation biofuels: CIBM, WIBM, SIBM, CIBE, WIBE, and SIBE for the baseline (1981 – 1990) and the future climate change scenarios (based on the climate change scenarios given in section 3).

4.2 Investigation of the impact of climate change on energy crop yields - (Aim 1)

4.2.1 Corn

The CERES-Maize simulated the average potential grain and stover yields of corn under the baseline and different climate change scenarios described in section 3. The climate change scenarios were applied for the years 1981 – 1990 (10 years), which represent the baseline condition and run for the simultaneous effect of changing *T*, *P*, and *[CO_2]*. In Tables 4.1 and 4.2 results of the simulated average potential grain yield under climate change scenarios along with the average grain yield for the baseline scenario are presented. Simulated corn grain yield for the baseline scenario was 12984 kg ha^{-1}, which is more than the simulated potential yield for all the climate change scenarios. CERES-Maize model output showed that simultaneous changes in *T*, *[CO_2]*, and *P* will have a negative effect on corn grain yield for all the climate change scenarios considered. The potential grain yield was predicted to decrease by 4% to 40% compared with the baseline scenario.

In all climate change scenarios, it was observed that the CERES-Maize simulation result showed increased potential corn grain yield under the impact of rising *[CO_2]*. For instance, under (*T* = +1.5 ^oC; *P* = +20%; and *[CO_2]* = 400 ppm) scenario, corn grain yield was reduced by about 9% compared with the baseline yield; however, under (*T* = +1.5 ^oC; *P* = +20%; and *[CO_2]* = 680 ppm), corn grain yield was reduced by about 4% compared with the baseline yield. These suggest some positive impact of increasing *[CO_2]* on corn grain yield, probably due to CO_2 fertilization.

Similarly, corn biomass (stover) yield exhibited similar patterns to those of corn grain in response to changes in *T*, *P*, and *[CO_2]*. Simulated corn stover yield for the baseline scenario was 11404 kg ha^{-1}. In contrast, corn stover yield was predicted to decrease and also increase under some climate change scenarios. Reduction in stover yield range from -1 to -18% relative to baseline condition under some scenarios (at *T* = +1.5 to +3.0 ^{o}C), and on the other hand, under some climate change scenarios corn stover yield was predicted to increase by +1 to +2% compared with the baseline scenario. For instance, at (*T* = +5 ^{o}C; *P* = -20%; and $[CO_2]$ = 400 ppm) scenario, corn stover showed a yield decrease of -18%, whilst at (*T* = +1.5 ^{o}C; *P* = +20%; and $[CO_2]$ = 680 ppm) scenario corn stover yield was predicted to increase by +2% compared with the baseline scenario.

4.2.1.1 Corn grain

Table 4.1: CERES-Maize simulations of the impact of climate change scenarios on average potential grain yield (kg ha^{-1}) of corn at Gainesville, USA. The simulated average potential grain yield for the baseline scenario = 12984 kg ha^{-1}.

CO_2 (ppm)	Precipitation (%)	Temperature (^oC)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	-20	11567.9	11253	10710.2	10041.6	9513.5	8768.7	8101.1	7764.1
	-15	11688.4	11353.3	10882.4	10254.5	9725.7	8964.5	8219.4	7946.9
	-10	11745.6	11462.7	11005.7	10420.1	9937.2	9134.6	8375.1	8034.5
	-5	11771.8	11557.9	11083.7	10514.6	10071.2	9359.4	8522.2	8129
	5	11843.2	11607.1	11165.1	10637.5	10201.1	9536	8717	8302.4
	10	11874.6	11623.7	11181.5	10667.3	10266.2	9585.5	8819.8	8421.5
	15	11881.4	11639.7	11223.4	10679.3	10298.2	9636.7	8829.7	8487.6
	20	11884.1	11647.4	11232.3	10715.2	10311	9699.5	8895.4	8526.9
470	-20	11749.9	11466.1	10974.3	10293.4	9763.9	9068.1	8337.2	8026.5
	-15	11850.8	11569.6	11095.1	10565	10015.5	9211.3	8467	8156.5
	-10	11887.5	11662.9	11177.6	10682.8	10231.4	9424.3	8612.4	8258.4
	-5	11921.4	11712.7	11284.6	10761	10342.2	9631.8	8772.3	8386.9
	5	11955.1	11774.2	11343.9	10863	10418.9	9770.2	8981.9	8558.2
	10	11963.8	11801.3	11366.1	10872.4	10471.9	9836.4	9028.1	8676.9
	15	11968	11810.1	11374.6	10891.7	10489.5	9889	9058.2	8719.7
	20	11971.8	11816	11381.6	10909.2	10499.4	9925	9115.2	8785.8
540	-20	11956.2	11661.8	11201.4	10622.5	10098.9	9311.3	8543.6	8270.9
	-15	11992.9	11762.4	11278.1	10804.7	10316	9507.5	8744.6	8411.2
	-10	12019.8	11833.9	11403	10892.2	10471.2	9743.5	8901.3	8510.5
	-5	12045.5	11859.3	11437.1	10989.7	10548.2	9863.2	9064.5	8629.7
	5	12102.2	11890.2	11499.1	11061.3	10636.5	9999.6	9209.8	8789.3
	10	12118.5	11901.4	11508	11074.9	10657.7	10056.7	9261.7	8869.8
	15	12122.8	11907.3	11536.3	11076.5	10668.5	10087.9	9311.9	8907.2
	20	12110.4	11929.8	11515.9	11102.4	10697.9	10105.4	9349.5	8965.9
610	-20	12158.1	11883.9	11445.9	10980.7	10486.2	9628.2	8832.1	8512
	-15	12177.2	11958.1	11505.7	11072.3	10669.8	9867	9024	8659.7
	-10	12204	12001.4	11586.5	11135	10755.3	10064.3	9184.4	8805.1
	-5	12224.2	12043.3	11616.7	11195.3	10835.1	10143.8	9327.3	8941.1
	5	12267.8	12090	11663.1	11232.7	10885.5	10272.1	9460.9	9084.5
	10	12260.8	12096.9	11675.2	11250.5	10884.9	10305.2	9531.3	9137.5
	15	12266.1	12100.7	11702.1	11259.7	10911.6	10329.6	9563.4	9186.7
	20	12266.5	12104.4	11705.1	11265	10937.4	10347.9	9584.8	9248.6
680	-20	12305.7	12120.6	11653.7	11230.8	10846.1	9978.4	9152.2	8770.7
	-15	12316	12176.8	11746.3	11274.1	10926	10203.8	9338.3	8934.4
	-10	12339.3	12224.6	11795	11351.2	11000.9	10325.5	9523.4	9096.3
	-5	12338.4	12243	11832.8	11369.9	11068.4	10387.8	9577.6	9207.6
	5	12368.2	12269.4	11858.6	11403.5	11112.7	10507.6	9713.6	9356.4
	10	12373.7	12288.6	11863.6	11427.7	11123.7	10535.5	9755.2	9410.2
	15	12379.3	12280.8	11883.1	11432.9	11141.8	10578.5	9780.1	9456.4
	20	12410.8	12312.4	11885.6	11435	11151.9	10606.5	9803.5	9486.7

4.2.1.2 Corn stover

Table 4.2: CERES-Maize simulations of the impact of climate change scenarios on average potential stover (biomass) yield (kg ha^{-1}) of corn at Gainesville, USA. The simulated average stover yield for the baseline scenario = 11404 kg ha^{-1}.

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	-20	11060.5	10898.4	10834.8	10639.9	10401.6	10061.9	9862.4	9334.7
	-15	11092.2	10966.6	10905.4	10728.6	10482.6	10172.9	9968.5	9423.6
	-10	11137.7	10994.2	10969.4	10833.1	10587.9	10230.1	10061.2	9514.5
	-5	11158.8	11028.9	10970.8	10877.8	10669	10329.1	10123.2	9597.4
	5	11253.2	11122.6	11054.8	10934.5	10730.6	10428.4	10272.6	9728.5
	10	11287.3	11177.7	11116	10982.7	10760.4	10475.4	10280.6	9742.3
	15	11299.2	11206.3	11169	11042.8	10821.4	10517.6	10335.7	9779.5
	20	11307.4	11222.8	11211.6	11099.9	10888.2	10540	10368.6	9814
470	-20	11191.4	11051.8	10992.3	10832	10608.1	10301.1	10073.4	9516.3
	-15	11216.9	11106.9	11041.6	10928.4	10685.7	10375	10174.2	9627.2
	-10	11251.8	11119.4	11095.3	10985.9	10784.8	10473.3	10269.2	9711.5
	-5	11288	11151.8	11121.1	10998.7	10835.4	10562.1	10360.7	9800.3
	5	11370.3	11254	11201.1	11074.4	10918.3	10595.3	10455.8	9903.2
	10	11390.7	11292.1	11263.9	11140.1	10935.1	10642.7	10482.9	9921.4
	15	11395.4	11314.2	11304.2	11198.7	10996.7	10651.1	10540.1	9964.5
	20	11402.4	11317.6	11322.3	11240.9	11058.2	10712	10564.9	10024.4
540	-20	11298.7	11191.2	11131.9	11027.5	10795	10502.8	10332	9732.8
	-15	11332.5	11202.3	11195.9	11080.1	10870.5	10583.1	10406.2	9819.2
	-10	11358	11236.1	11215.9	11129.9	10940.9	10677.3	10497	9932.2
	-5	11411.3	11270.9	11249.3	11149.4	10973.4	10716.5	10593.8	10007.4
	5	11457.1	11372.8	11343.8	11227.1	11045.5	10763.8	10638.7	10107.5
	10	11464.2	11394.8	11388.8	11287.8	11105.6	10762.3	10697	10129.1
	15	11471.4	11398.3	11408.6	11334.1	11164.5	10816.9	10700.8	10193
	20	11482	11408.4	11417	11351.4	11209.8	10872.8	10763.5	10228.7
610	-20	11412.2	11302.7	11301	11201.3	11003.7	10728.6	10586.2	10004.4
	-15	11435.8	11329.1	11342	11238.2	11082	10794.2	10664.4	10079
	-10	11470.5	11354.8	11351.9	11270.9	11125.8	10840.8	10763.9	10188.2
	-5	11516.3	11421	11384.3	11321.9	11138.7	10860.8	10796.4	10264.4
	5	11539.8	11466.1	11480.5	11404.8	11220.4	10903	10863.8	10345.7
	10	11550.9	11472.9	11508	11449.9	11284.2	10933.1	10868.5	10400.9
	15	11562.9	11484.7	11511	11467.5	11327.1	10989.8	10911.9	10425.8
	20	11567.9	11502.8	11520.5	11479.7	11347.4	11046.7	10971	10452.5
680	-20	11506.5	11415.4	11432.9	11322.5	11193.3	10903.3	10806.3	10249.5
	-15	11527.8	11431.5	11440.2	11385	11220.4	10959.6	10887.8	10338.5
	-10	11575.6	11469.6	11469	11413.8	11250.2	10981.5	10963.1	10419
	-5	11597.6	11516.6	11527.1	11445.5	11277.3	10992.8	10987	10484.9
	5	11622.2	11537.6	11580.4	11548	11370.7	11043.6	11048.3	10550.5
	10	11628.2	11552.1	11586	11574.6	11424.7	11087.1	11050.6	10587.2
	15	11633	11565	11596.9	11585.1	11457.7	11142.9	11104.2	10602
	20	11638.1	11571.6	11614.1	11591.5	11463.8	11173	11160	10657.7

4.2.2 Soybean

The CROPGRO-Soybean simulated the average potential seed and stalks yield of soybean under the baseline and climate change scenarios described in the previous section (Chapter 3). Similar to corn, the climate change scenarios were applied for the years 1981-1990 (10 years), which represent the baseline condition and run for the simultaneous effect of changing *T*, *P*, and *[CO_2]*. Simulation results for the soybean seed and stalk yields are presented in Tables 4.3 and 4.4 respectively. Simulated average potential soybean seed yield for the baseline scenario was 3972 kg ha^{-1}. The prediction results of soybean under climate change scenarios showed that soybean seed yield will both decrease and increase in some climate scenarios under the influence of combined changes in *T*, *P*, and *[CO_2]* compared with the baseline scenario. The reduction in the potential seed yield due to the impact of climatic conditions exhibited an increasing trend, which range from -0.8 to -59%. Similarly, the predicted increase in soybean seed yield range from +0.4 to 21.1%. Results also showed that increased atmospheric *[CO_2]* would have positive impact on the yield of soybean. For instance, under (*T* =1.5; *P* = +20; and *[CO_2]* = 400 ppm), soybean seed yield was predicted to increase by +2.2%. However, under (*T* = 1.5; *P* = +20; and *[CO_2]* = 680 ppm), soybean seed yield was predicted to increase by +21.1% compared with the baseline scenario. This suggests that rising atmospheric levels of CO_2 would enhance the seed yield of soybean.

Unlike soybean seed, model prediction results showed that predicted climate changes would have a positive impact on soybean stalk yield in all climate change scenarios studied. Simulated average potential soybean stalks yield for the baseline scenario was 2330 kg ha^{-1}. Model prediction showed that he average soybean stalks yield would increase by +2.7 to 34.9% compared with the baseline scenario.

4.2.2.1 Soybean seed

Table 4.3: CROPGRO-Soybean simulations of the impacts of climate change scenarios on average potential seed yield (kg ha^{-1}) of soybean at Gainesville, USA. The simulated average seed yield for the baseline scenario = 3927 kg ha^{-1}.

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	-20	3441.4	3287.4	3089.3	2923.5	2650.3	2432.7	2188.6	1929
	-15	3591.2	3434.2	3225.7	3038.9	2799.1	2539.2	2291.1	2001.3
	-10	3695.4	3531.2	3336.5	3159.6	2903.5	2655.6	2361.6	2083
	-5	3809	3652	3458.7	3255.7	3008.7	2751.2	2480.7	2146.2
	5	3945.7	3791.7	3643.9	3466.7	3208.1	2946.6	2634.5	2268.8
	10	3978.2	3844.8	3707.5	3521.6	3284.6	3007	2688.3	2313.8
	15	3999.3	3873.5	3740.1	3569.6	3354.3	3073.9	2754.1	2370.5
	20	4017.4	3896.8	3780.8	3595.7	3378.8	3111.3	2787.2	2416.5
470	-20	3784	3623.6	3439.2	3228.8	2940.6	2692.5	2427.6	2136.7
	-15	3940.1	3775.8	3560.3	3366.4	3083.9	2817.5	2544.7	2238.2
	-10	4053.6	3878.4	3684.6	3473.8	3220.9	2939.8	2636.4	2308.6
	-5	4183.1	4009	3813.2	3589.3	3346.5	3054.5	2745.3	2383.7
	5	4311.7	4162.9	4009.7	3806.9	3533	3253.5	2911.2	2519.4
	10	4339.7	4202.7	4063.4	3878.7	3614.7	3311.7	2974.3	2559
	15	4369.5	4225.6	4103	3914.3	3683.7	3380.7	3025.9	2619.6
	20	4382.5	4254.5	4131.8	3948.5	3716.8	3421.9	3074.3	2666.6
540	-20	4038.2	3856	3680.2	3466.3	3146.8	2891.5	2596.8	2286.7
	-15	4189.7	4029.5	3792.5	3578.5	3306.4	3012.4	2719.6	2402.2
	-10	4333.1	4152.5	3840	3705.1	3435.4	3142.5	2826.5	2492.5
	-5	4451.8	4270.9	4060.3	3831.7	3573.2	3263	2945.7	2554.6
	5	4577.2	4426.7	4267.9	4057.7	3770.5	3483.1	3118.9	2703.8
	10	4603.3	4461.1	4318.2	4126.1	3865.7	3537.1	3174	2735.2
	15	4632.3	4500.7	4359.2	4163.2	3926	3615.8	3237.1	2799.9
	20	4646.2	4519.1	4390.2	4203.4	3956.6	3649	3286.5	2844.3
610	-20	4216.7	4025.7	3864.6	3629	3313.4	3023.7	2725.3	2397.8
	-15	4376.1	4209.6	3963.5	3761.3	3456.1	3156.8	2848.5	2518.3
	-10	4520.3	4335.1	4122	3890.1	3595.8	3287.6	2959.2	2610.7
	-5	4642.2	4467.3	4246.9	4013.4	3736.7	3422.6	3083.7	2674.5
	5	4765.8	4612.8	4447.8	4236.2	3939.9	3639.7	3257.7	2829.8
	10	4792.7	4647.6	4499.1	4301.7	4037.4	3695.6	3316	2865.7
	15	4826	4681.5	4538	4341.9	4094	3768.2	3384.7	2923.4
	20	4837.4	4699.6	4571.4	4381.9	4128.1	3809.4	3436.1	2967.6
680	-20	4347.1	4146	3985.9	3749.8	3414.9	3135.1	2813.5	2481.8
	-15	4507.5	4326.6	4089.7	3886.3	3577	3256.2	2943.6	2603.2
	-10	4656.6	4465.6	4248.9	4015.7	3710.4	3395.5	3067.1	2698.6
	-5	4776	4598.4	4379.3	4138.1	3852.3	3531.9	3178.6	2769
	5	4902.9	4730.6	4577.7	4360.8	4063.9	3751	3365.7	2920.4
	10	4929.4	4777.9	4628	4428.9	4158.5	3811.3	3422.7	2966.2
	15	4959.8	4812.8	4680	4466.1	4214.3	3890.9	3489.1	3029.8
	20	4976.8	4830.3	4704.2	4511.5	4248.7	3923.3	3536.7	3065.5

4.2.2.2 Soybean stalks

Table 4.4: CROPGRO-Soybean simulations of the impacts of climate change scenarios on average potential stalks yield (kg ha^{-1}) of soybean at Gainesville, USA. The simulated average stalks yield for the baseline scenario = 2330 kg ha^{-1}.

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
400	**-20**	2503	2518	2547	2555	2555	2514	2454	2395
	-15	2517	2537	2575	2593	2598	2570	2527	2480
	-10	2537	2563	2605	2613	2635	2614	2581	2570
	-5	2557	2581	2623	2646	2670	2661	2637	2612
	5	2576	2613	2666	2701	2736	2749	2740	2737
	10	2589	2623	2672	2726	2764	2776	2776	2784
	15	2588	2630	2686	2743	2787	2815	2816	2831
	20	2591	2633	2689	2748	2800	2840	2860	2878
470	**-20**	2748	2769	2795	2807	2814	2777	2710	2661
	-15	2762	2784	2824	2847	2857	2831	2798	2759
	-10	2789	2813	2849	2878	2894	2879	2848	2840
	-5	2804	2835	2877	2914	2929	2929	2903	2887
	5	2822	2863	2923	2960	2996	3017	3011	3022
	10	2834	2874	2928	2990	3022	3039	3044	3069
	15	2835	2878	2935	3000	3047	3086	3087	3119
	20	2836	2881	2944	3006	3061	3106	3130	3161
540	**-20**	2919	2941	2974	2987	2997	2959	2893	2852
	-15	2935	2958	3000	3037	3044	3017	2982	2951
	-10	2955	2983	2954	3058	3073	3064	3035	3046
	-5	2973	3007	3054	3089	3112	3109	3097	3081
	5	2996	3039	3099	3138	3174	3199	3200	3224
	10	3007	3047	3103	3166	3209	3224	3233	3266
	15	3006	3051	3109	3178	3230	3266	3277	3314
	20	3013	3056	3118	3181	3240	3286	3314	3356
610	**-20**	3041	3060	3094	3115	3121	3087	3027	2986
	-15	3058	3081	3124	3154	3170	3145	3115	3088
	-10	3073	3107	3143	3187	3199	3192	3167	3183
	-5	3095	3122	3179	3209	3239	3240	3226	3215
	5	3121	3159	3224	3266	3298	3326	3329	3361
	10	3128	3172	3225	3290	3333	3351	3362	3397
	15	3127	3172	3232	3304	3358	3390	3406	3454
	20	3133	3177	3242	3305	3370	3414	3444	3491
680	**-20**	3121	3147	3181	3205	3212	3175	3116	3083
	-15	3143	3168	3212	3241	3261	3235	3204	3184
	-10	3157	3191	3233	3275	3288	3285	3261	3274
	-5	3179	3208	3264	3299	3330	3330	3316	3317
	5	3205	3237	3312	3357	3388	3415	3423	3456
	10	3215	3259	3312	3377	3423	3442	3455	3499
	15	3210	3260	3320	3391	3448	3481	3502	3548
	20	3217	3265	3328	3392	3459	3503	3534	3585

4.2.3 Wheat

The CERES-Wheat simulated the average potential grain and straw yields of wheat under baseline and future climate change scenarios as described in Chapter 3. The climate change scenarios were applied for the years 1981-1990 (10 years), which represent the baseline condition and run for the combined effect of changing *T*, *P*, and *[CO_2]*. In Tables 4.5 and 4.6 results of the simulated average potential grain yield under climate change scenarios along with the average grain yield for the baseline scenario are presented. Simulated wheat grain and straw yields for the baseline scenario was 5955 kg ha^{-1} and 5895 kg ha^{-1} respectively. The prediction results of the CERES-Wheat showed that wheat grain would increase under the influence of future climate changes (combined changes in *T*, *[CO_2]*, and *P*) in all climate changes scenarios. The potential wheat grain yield was predicted to increase by +2.5 to 25.7% compared with the baseline scenario.

In contrast, compared with the baseline scenario, the prediction results of wheat straw yield under climate change showed that wheat straw yield would both decrease and increase in some climate change scenarios under the influence of combined changes in *T*, *P*, and *[CO_2]*. This means that the predicted climate changes will have both negative and positive impact on wheat straw yield. Model prediction showed that the reduction rate in wheat straw yield was variable between -2.7 and -34.9%. Among the entire climate changes used in the study, increased atmospheric *[CO_2]* also showed increased in straw yield similar to grain yield.

4.2.3.1 Wheat grain

Table 4.5: CERES-Wheat simulations of the impacts of climate change scenarios on average potential grain yield (kg ha^{-1}) of wheat at Rothamsted, UK. The simulated average grain yield for the baseline scenario = 5955 kg ha^{-1}.

CO_2 (ppm)	Precipitation (%)	Temperature (°C)				
		0.5	1.5	2.5	3.5	4.5
400	-20	6807	7388	7633	7805	7475
	-10	6717	7294	7546	7716	7407
	10	6341	6975	7209	7446	7195
	20	6106	6767	7016	7283	7064
540	-20	7213	7700	7755	7947	7665
	-10	7091	7583	7646	7854	7594
	10	6663	7254	7344	7595	7376
	20	6409	7045	7159	7436	7247
680	-20	7582	7941	7850	8018	7731
	-10	7430	7821	7754	7937	7663
	10	7008	7474	7458	7691	7475
	20	6739	7253	7286	7544	7350

4.2.3.2 Wheat straw

Table 4.6: CERES-Wheat simulations of the impacts of climate change scenarios on average potential straw yield (kg ha^{-1}) of wheat at Rothamsted, UK. The simulated average straw yield for the baseline scenario = 5895 kg ha^{-1}.

CO_2 (ppm)	Precipitation (%)	Temperature (°C)				
		0.5	1.5	2.5	3.5	4.5
400	-20	5768	5631	6568	7559	8646
	-10	5846	5707	6690	7641	8638
	10	5746	5717	6769	7759	8732
	20	5751	5645	6729	7750	8729
540	-20	5850	5792	7183	8417	9481
	-10	5875	5899	7304	8545	9578
	10	5811	5809	7335	8567	9578
	20	5707	5817	7337	8564	9580
680	-20	5911	5970	7635	9089	10028
	-10	5879	6025	7730	9154	10058
	10	5859	6013	7780	9209	10054
	20	5709	5983	7756	9178	9984

4.3 Investigation of the impacts of climate change on life cycle GHG emissions of first-generation biofuels - (Aim 2)

Life cycle GHG emissions savings for bioethanol from corn, CBE; and wheat, WBE; and biodiesel from soybean, CBE life cycle models were calculated for the baseline and future climates. Trends in the change in potential life cycle GHG emissions savings of CBE, WBE, and SBD under baseline and the future climate change scenarios were compared using a scatter plots as shown in Figures 4.1 to 4.3.

4.3.1 Corn bioethanol (CBE)

Life cycle GHG emissions savings were calculated under the baseline and future climate change scenarios by the CBE model. Model output results presented in Appendix A were plotted to analyze the trend in life cycle GHG emissions savings under different scenarios (see Figure 4.1). The calculated life cycle GHG emissions savings for CBE from the baseline period was -4743.32 kg CO_2-equiv. ha^{-1}. Compared with the baseline, the calculated life cycle GHG emissions savings for CBE life cycle model decreased in all the climate change scenarios. The predicted reduction in the life cycle GHG emissions savings for CBE ranges from -4.2 to -46.1%. Air surface temperature, *T*, had the largest impact on the life cycle GHG emissions savings of CBE. In general, for CBE, the higher the temperature, the higher the reduction in the potential life cycle GHG emissions savings. For example, at ($[CO_2]$ = 400 ppm; *P* = -20%; *T* = +1.5 ^oC) scenario, reduction in the GHG emissions savings for CBE was -12.1% compared with the baseline scenario. However, at ($[CO_2]$ = 400 ppm; *P* = -20%; *T* = +3.5 ^oC) and ($[CO_2]$ = 400 ppm; *P* = -20%; *T* = +5 ^oC) scenario, compared with the baseline scenario, the reduction in the life cycle GHG emissions savings was -30% and -46.1% respectively.

Similarly, results indicated that life cycle GHG emissions savings of CBE would be affected by changes in precipitation amount, *P*. For instance, at (*P* = -20%; *T* = +2 ^oC; $[CO_2]$ = 400 ppm) and (*P* = +20%; *T* = +2 ^oC; $[CO_2]$ = 400 ppm) the predicted reduction in the life cycle GHG emissions savings for CBE was -19% and -15% respectively. This suggests that increased *P* would minimize the reduction in the life cycle GHG emissions savings of CBE.

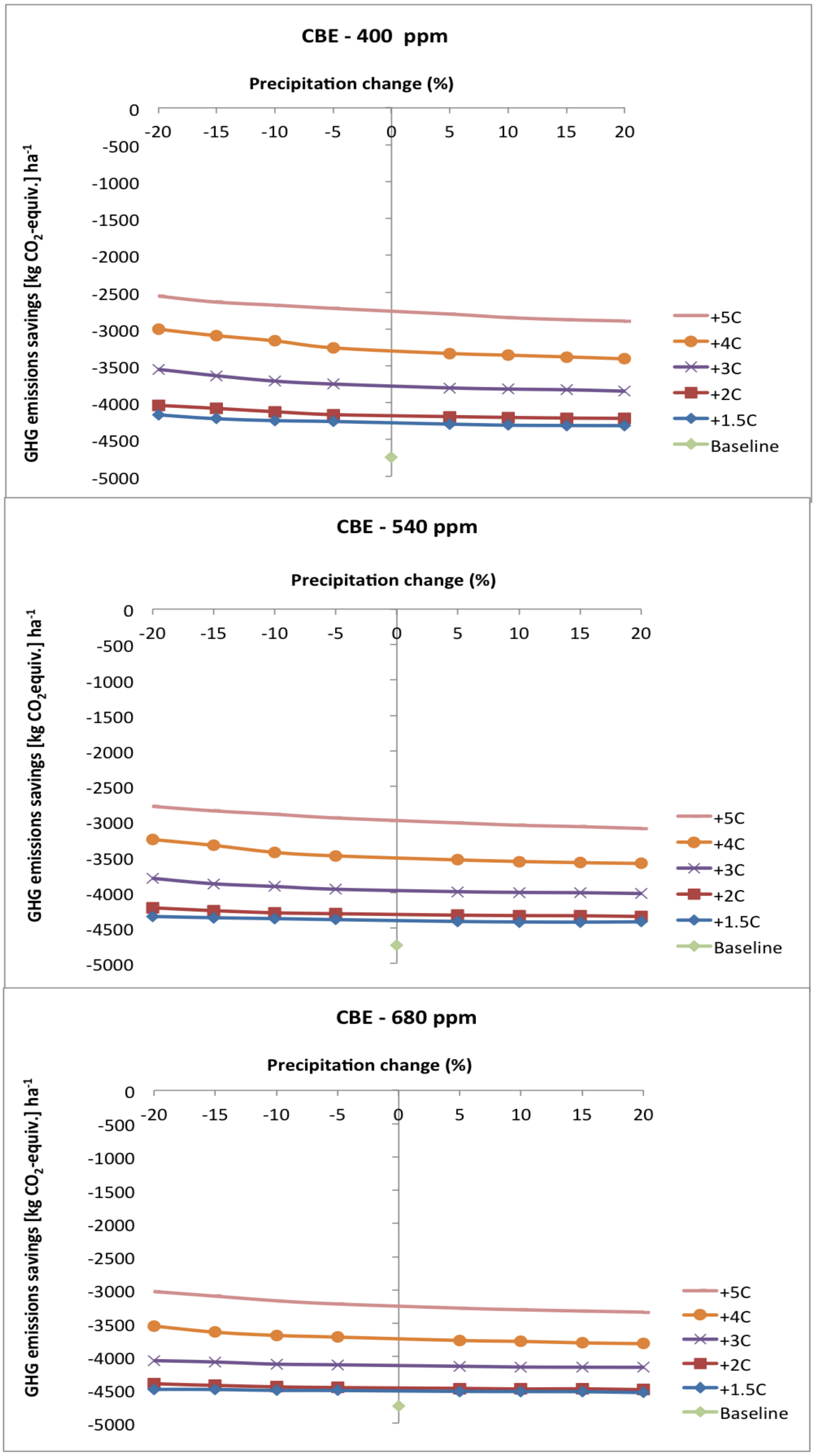

Figure 4.1: Calculated life cycle GHG emissions savings of CBE (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of CBE from the 1981 - 1990 baseline scenario is also shown.

4.3.2 Wheat bioethanol (WBE)

For WBE model, life cycle GHG emissions savings results presented in Appendix B were plotted for both the baseline and future climate change scenarios (see Figure 4.2). The calculated life cycle GHG emissions savings from the baseline period was -2776.1 kg CO_2-equiv. ha^{-1}. Unlike CBE, WBE life cycle model results showed that life cycle GHG emissions savings for WBE would increase under future climate change scenarios (see Figure 4.2). Compared with the baseline period, the life cycle GHG emissions savings was predicted to increase by +2.5 to 33.5% in future climate periods. Unlike CBE, increased *T* coupled with decreased *P* and increased *[CO₂]* was predicted to have positive impact on potential life cycle GHG emissions savings for WBE. For instance, at (T = +0.5 ^{o}C; P = +20%; $[CO_2]$ = 400 ppm) scenario, the potential life cycle GHG emissions savings was predicted to increase by +2.5 compared with the baseline period. But, at (T = +3.5 ^{o}C; P = +20%; $[CO_2]$ = 400 ppm) and (T = +4.5 ^{o}C; P = +20%; $[CO_2]$ = 400 ppm) compared with the baseline period, the potential life cycle GHG emissions savings for WBE was predicted to increase by +23.3%. Furthermore, at (T = +0.5 ^{o}C; P = -20%; $[CO_2]$ = 540 ppm) and (T = +0.5 ^{o}C; P = +20%; $[CO_2]$ = 540 ppm) scenario, the potential life cycle GHG emissions savings for WBE was predicted to increase by +19.7% and +7.7% respectively. This means that WBE responds positively to reducing precipitation amounts with increasing temperature and atmospheric CO_2 levels.

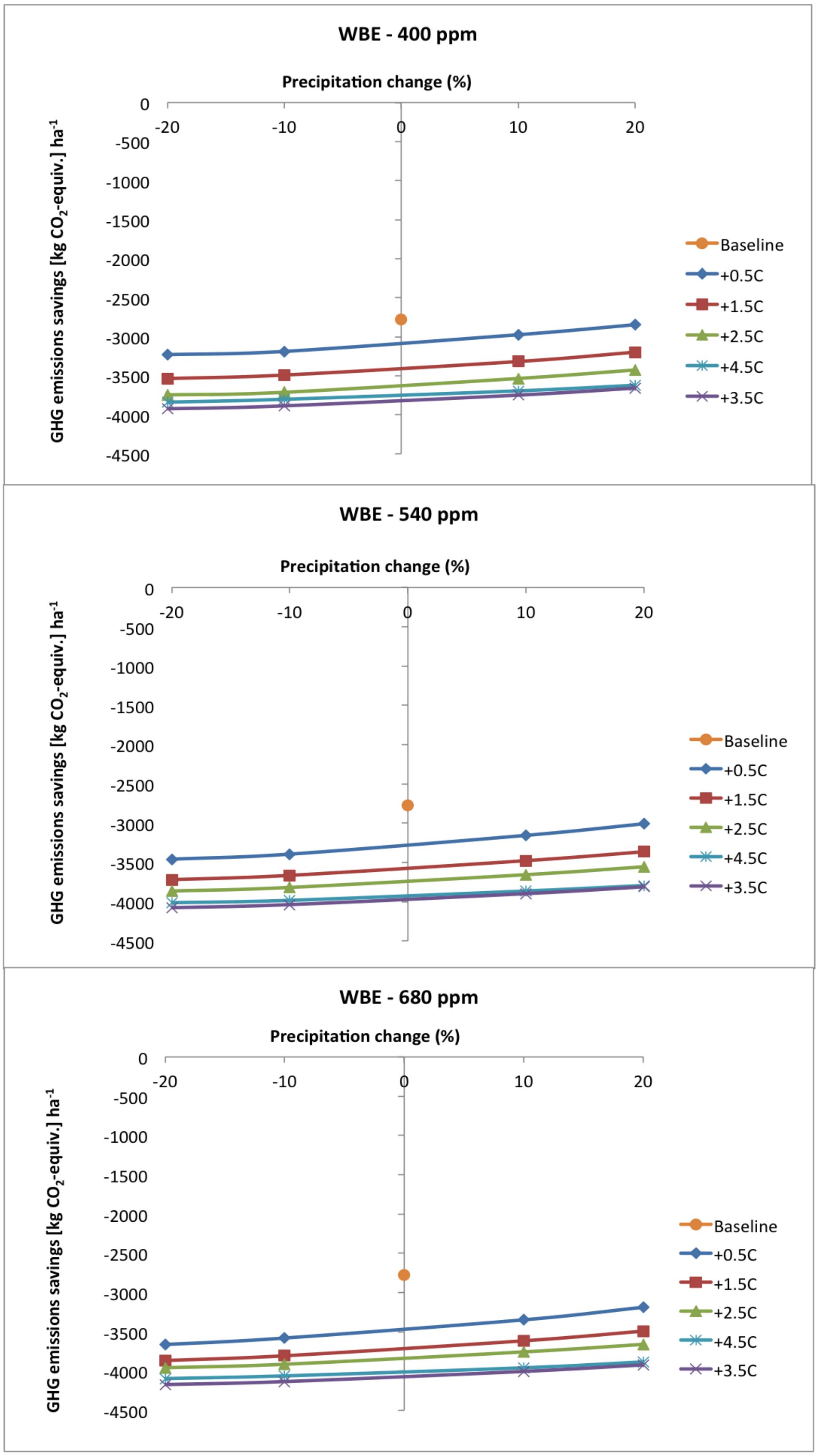

Figure 4.2: Calculated life cycle GHG emissions savings of WBE (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of WBE from the 1981 - 1990 baseline scenario is also shown.

4.3.3 Soybean biodiesel (SBD)

The life cycle GHG emissions savings results of SBD model are presented in Appendix C. Trends in the change in potential life cycle GHG emissions savings of SBD in climate change scenarios are presented in Figure 4.3, along with the life cycle GHG emissions savings from the baseline period. The calculated life cycle GHG emissions savings from the baseline period was -2655.41 kg CO_2-equiv. ha^{-1}. However, SBD model output showed that increasing *T*, *P*, and *[CO_2]* will have both positive and negative effect on life cycle GHG emissions savings of SBD production chain. A +0.22 to +27% increase and -0.7 to -60.8% decrease in the life cycle GHG emissions savings of SBD was predicted across the future climate change scenarios compared with the baseline period. When *[CO_2]* = 400 ppm and *T* = +1.5 ^{o}C, only increased *P* from +5% to +20% had positive impact on the life cycle GHG emissions of SBD from +1.3 to +3.6% compared with the baseline scenario. But when *[CO_2]* = 540 and 680 ppm, the life cycle GHG emissions savings increases with increasing *[CO_2]*, *T*, and *P*. Reductions in *P* amounts have been shown to have positive impact on the GHG emissions savings of SBD under certain conditions. For instance, at (*P* = -5%; *T* = +2.5 ^{o}C; *[CO_2]* = 540 ppm) and (*P* = -20%; *T* = +3.5 ^{o}C; *[CO_2]* = 680 ppm) scenarios, +6% and +4.1% increase was predicted respectively compared with the baseline period. This suggests some improvements in the life cycle GHG emissions savings of SBD with increased *[CO_2]* coupled with increased *P*, and *T*. However, increased *T* above +4 ^{o}C will have negative impact on the GHG emissions savings even if there is increase in *[CO_2]* and *P*.

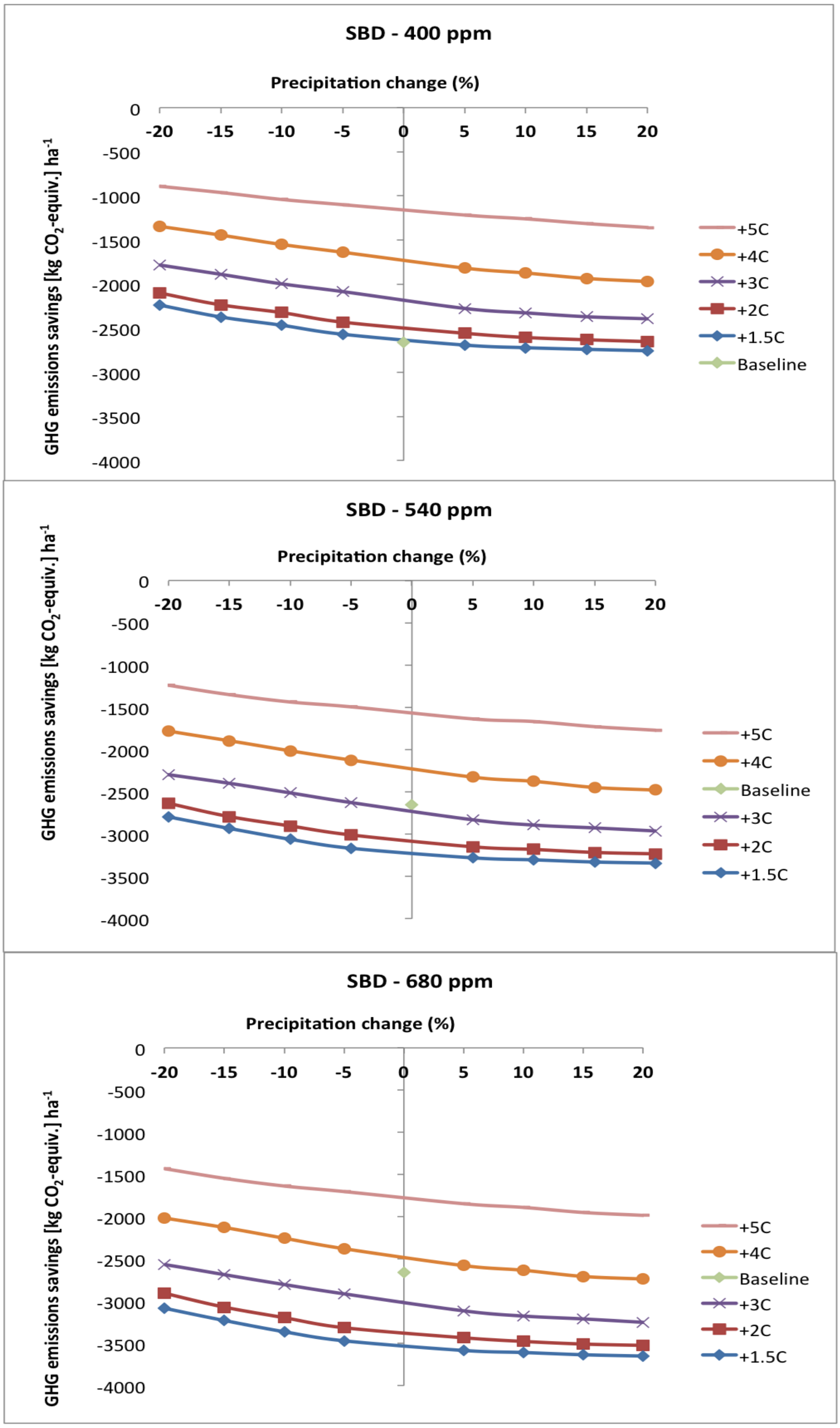

Figure 4.3: Calculated life cycle GHG emissions savings of SBD (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of SBD from the 1981 - 1990 baseline scenario is also shown.

4.4 Investigation of the impacts of climate change on life cycle GHG emissions of second-generation biofuels - (Aim 3)

Simulated potential life cycle GHG emissions savings of second-generation biofuel production chains from corn: CIBM and CIBE; wheat: WIBM and WIBE, and soybean: SIBM and SIBE are presented in this sub-section. The potential life cycle GHG emissions savings were calculated for the baseline condition and future climates period. Charts were plotted using the models output data presented in Appendices D – I.

Presented in Appendices D, E, and F are the life cycle GHG emissions savings results of CIBM, SIBM, and WIBM, respectively. And the life cycle GHG emissions savings results of CIBE, SIBE, and WIBE are presented in Appendices G, H, and I respectively.

4.4.1 Corn integrated biomethanol (CIBM) & corn integrated bioelectricity (CIBE)

Trends in the change in potential life cycle GHG emissions savings of CIBM and CIBE with the main effects of climate change scenarios are presented in Figures 4.4 and 4.5 respectively. Model outputs showed that net life cycle GHG emissions savings of -8573.31 kg CO_2-equiv. ha^{-1} and -10996.7 kg CO_2-equiv. ha^{-1} could be achieved for CIBM and CIBE, respectively for the baseline period. However, under climate change, model prediction showed that combined changes in *T*, *P*, and *[CO_2]* would have negative impact on the potential life cycle GHG emissions savings of both CIBM as well as CIBE. Compared with the baseline scenario, the life cycle

GHG emissions savings of CIBM would decline by -2.6 to -37.7%, whilst CIBE would decline by -1.6 to -33.4%. As expected, the scenarios of increasing T had the highest impact on life cycle GHG emissions savings for CIBM and CIBE, particularly under scenarios with decreasing P. For example, CIBM at (P = +20%; T = +1.5 ^oC; $[CO_2]$ = 400 ppm), (P = +20%; T = +5 ^oC; $[CO_2]$ = 400 ppm), (P = -20%; T = +1.5 ^oC; $[CO_2]$ = 400 ppm), and (P = -20%; T = +5 ^oC; $[CO_2]$ = 400 ppm) scenarios had a -6.8%, -31.6%, -9.5%, and -37.7% reduction respectively, compared with the baseline scenario. Similarly, at (P = +20%; T = +1.5 ^oC; $[CO_2]$ = 400 ppm), (P = +20%; T = +5 ^oC; $[CO_2]$ = 400 ppm), (P = -20%; T = +1.5 ^oC; $[CO_2]$ = 400 ppm), and (P = -20%; T = +5 ^oC; $[CO_2]$ = 400 ppm) scenarios, CIBE had a -5.5%, -27.7%, -8.1%, and -33.4% reduction in life cycle GHG emissions savings respectively, compared with the baseline scenario. Model outputs also showed that scenarios of increasing $[CO_2]$ would have positive impact on life cycle GHG emissions savings of both CIBM and CIBE. Though still less than the value for the baseline scenario, increased $[CO_2]$ was predicted to reduce the negative impact of increased T. For instance, at ($[CO_2]$ = 400; P = -10%; T = +5 ^oC), ($[CO_2]$ = 540; P = -10%; T = +5 ^oC), and ($[CO_2]$ = 680; P = -10%; T = +5 ^oC) CIBM had a reduction of -35.9%, -31.3%, and -26.3% respectively, compared with the baseline scenario. The same pattern was also exhibited by CIBE, which had a reduction of -31.3%, -27.3%, and -22.4% respectively, under same scenarios. Scenarios of increasing P also were shown to have positive impact on life cycle GHG emissions savings of both CIBM as well as CIBE. For example, under ($[CO_2]$ = 540; P = -20%; T = +5 ^oC) and ($[CO_2]$ = 540; P = +20%; T = +5 ^oC) scenarios, CIBE had a reduction of -29.3% and -23.8% respectively, whilst CIBM had a reduction of -33.4% and -27.7% respectively, compared with the baseline period.

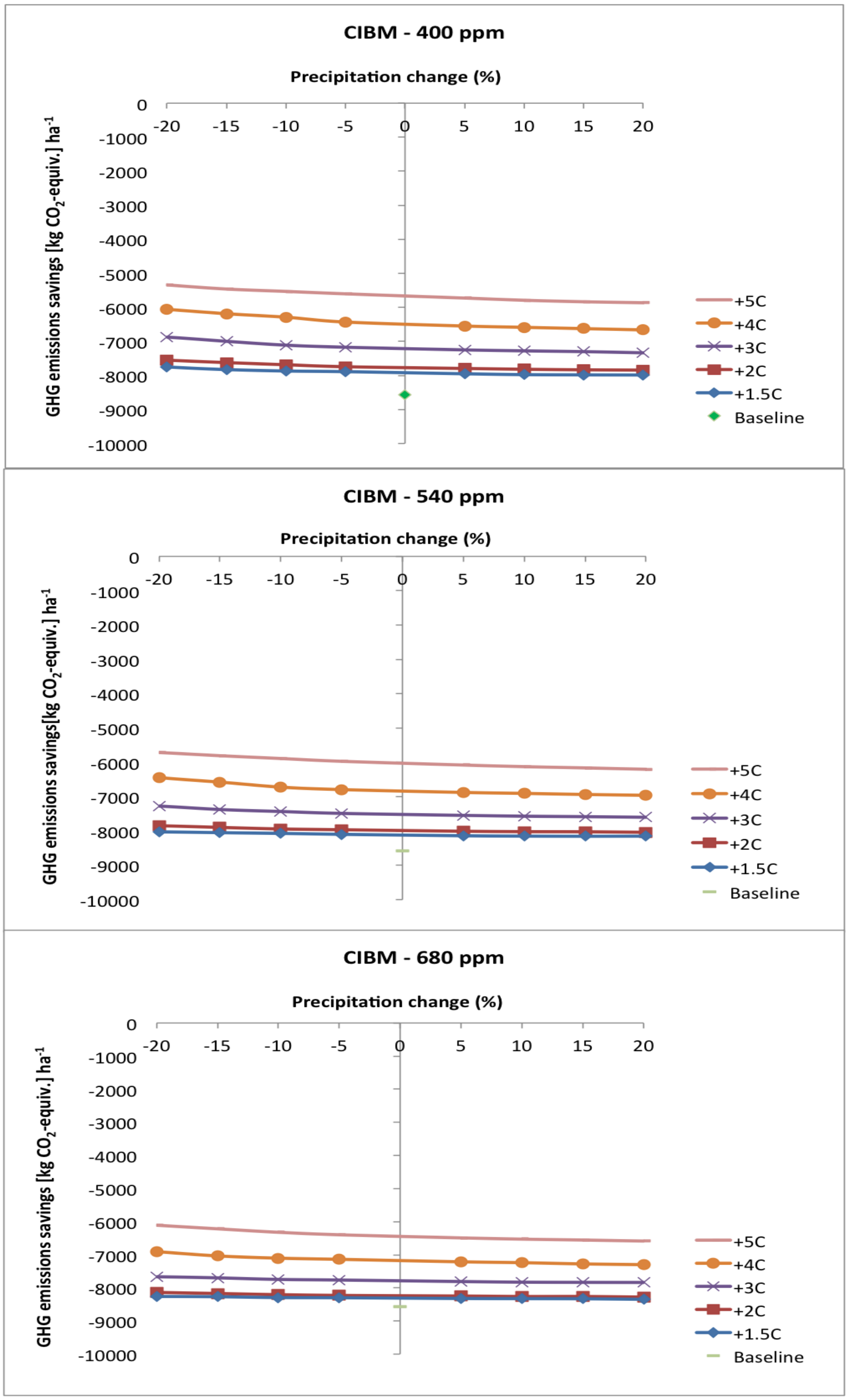

Figure 4.4: Calculated life cycle GHG emissions savings of CIBM (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of CIBM from the 1981 - 1990 baseline scenario is also shown.

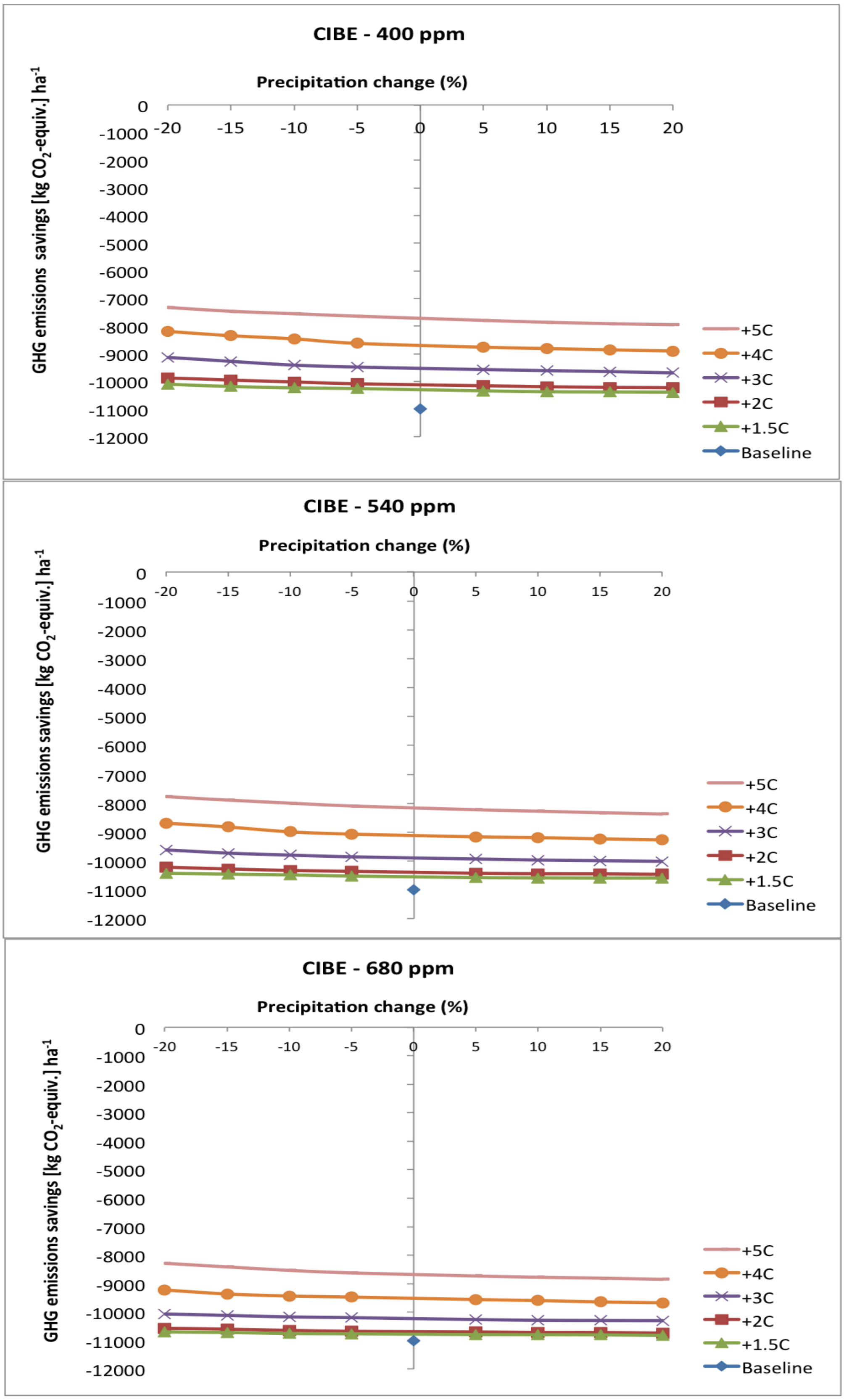

Figure 4.5: Calculated life cycle GHG emissions savings of CIBE (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of CIBE from the 1981 - 1990 baseline scenario is also shown.

4.4.2 Soybean integrated biomethanol (SIBM) & soybean integrated bioelectricity (SIBE)

For the trend of life cycle GHG emissions savings change for SIBM and SIBE, models output indicated that life cycle GHG emissions savings would be both positively as well as negatively affected across some scenarios of climate change. Models calculation showed that SIBM and SIBE had a net life cycle GHG emissions savings of -3441.1 kg CO_2-equiv. ha^{-1} and -1350.04 kg CO_2-equiv ha^{-1} respectively under the baseline scenario. Compared with the baseline period, SIBE was predicted to have between -0.1 to -82.6% reductions in life cycle GHG emissions savings. On the other hand, model predictions showed that reduction in life cycle GHG emissions savings for SIBM would range from -0.1 to -44.6%. Similarly, compared with the baseline period, increase in life cycle GHG emissions savings of SIBE and SIBM ranges between +0.1 to +31.6% and +0.1 to +28% respectively. For SIBE, highest reduction (-82.6%) was observed at ($[CO_2]$ = 400; P = -20%; T = +5 ^oC) scenario and lowest reduction (-0.1%) was recorded at ($[CO_2]$ = 680; P = -5%; T = +3.5 ^oC) scenario. Moreover, highest increase (+31.6%) in life cycle GHG emissions savings was recorded at ($[CO_2]$ = 680; P = +20%; T = +1.5 ^oC) and lowest increase (+0.1%) was recorded at ($[CO_2]$ = 540; P = +10%; T = +3.5 ^oC) for SIBE.

For SIBM, highest reduction (-44.6%) was observed at ($[CO_2]$ = 400; P = -20%; T = +5 ^oC) scenario and lowest reduction (-0.1%) was recorded at ($[CO_2]$ = 680; P = +15%; T = +5 ^oC) scenario. furthermore, highest increase (+28%) in life cycle GHG emissions savings was also recorded at ($[CO_2]$ = 680; P = +20%; T = +1.5 ^oC) and lowest increase (+0.1%) was recorded at ($[CO_2]$ = 540; P = +15%; T = +4.5 ^{o}C) for SIBM.

Clearly, as shown in Figures 4.6 and 4.7, it appears that the scenarios of increasing $[CO_2]$ and P will have a positive impact on life cycle GHG emissions savings of both SIBE and SIBM.

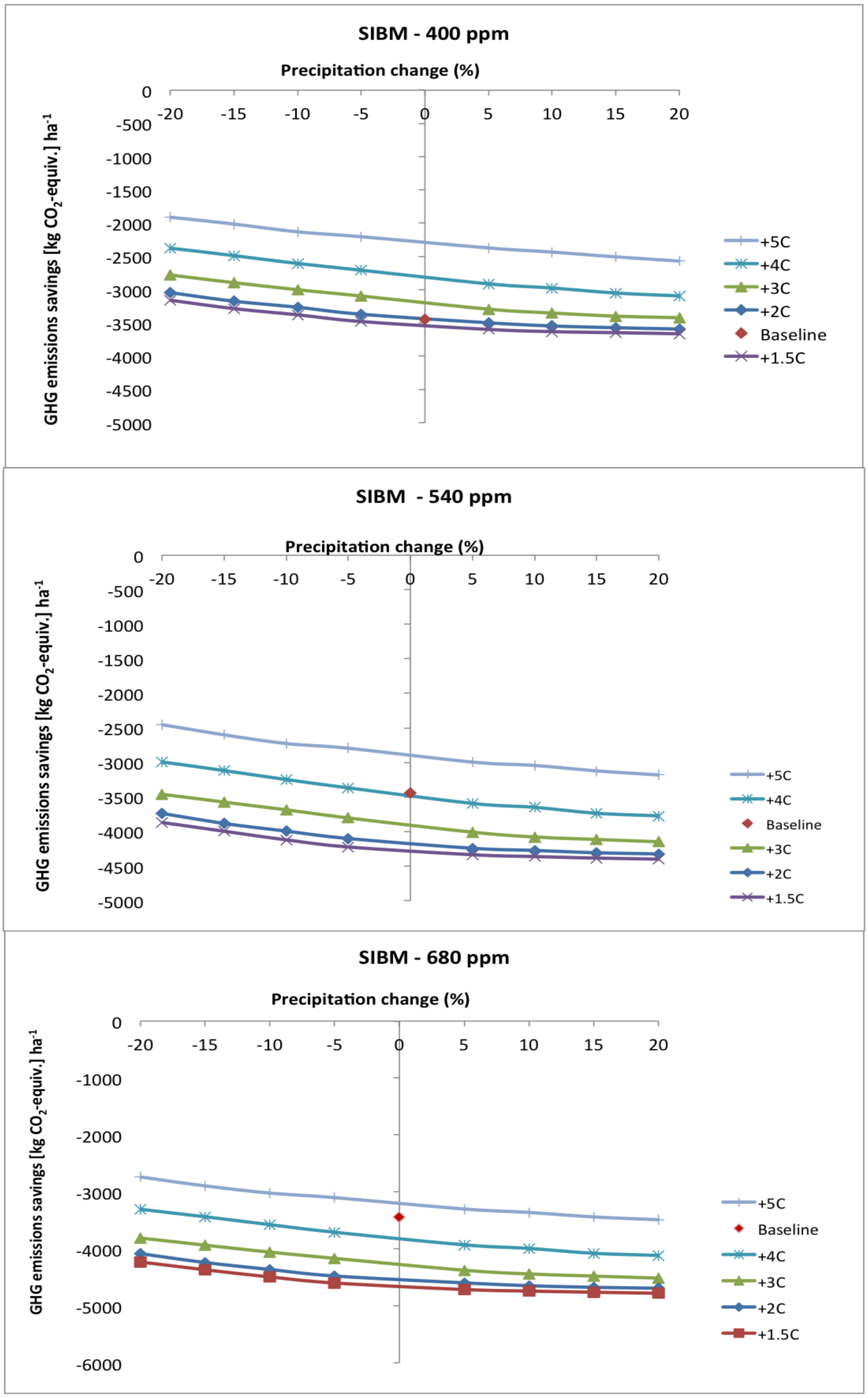

Figure 4.6: Calculated life cycle GHG emissions savings of SIBM (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of SIBM from the 1981 - 1990 baseline scenario is also shown.

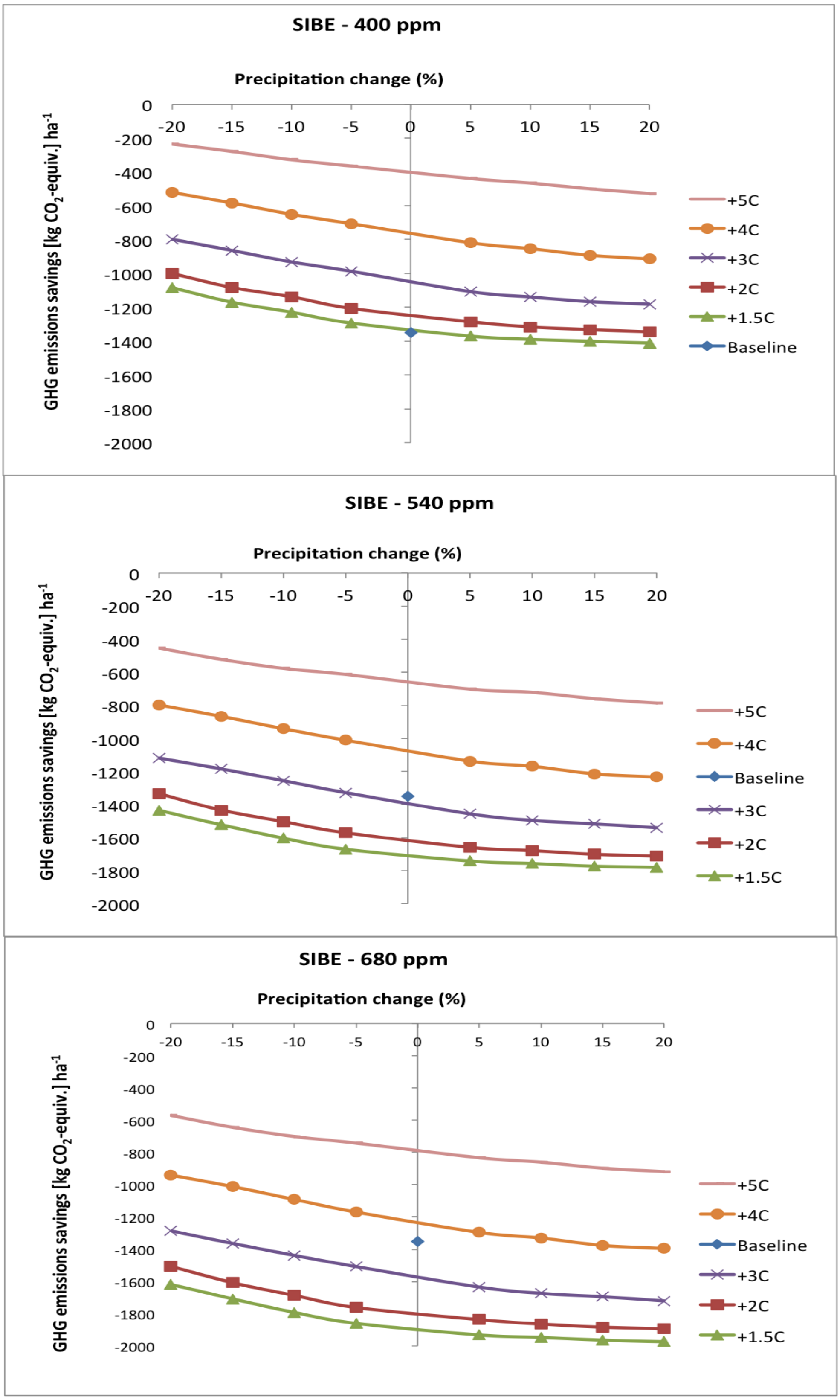

Figure 4.7: Calculated life cycle GHG emissions savings of SIBE (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of SIBE from the 1981 - 1990 baseline scenario is also shown.

4.4.3 Wheat integrated biomethanol (WIBM) & wheat integrated bioelectricity (WIBE)

For WIBM and WIBE productions chains, models calculation showed that WIBM had life cycle GHG emissions savings of -500.87 kg CO_2-equiv. ha^{-1} and WIBE had -4648.93 kg CO_2-equiv. ha^{-1} from the baseline scenario. However, models prediction showed that both WIBM & WIBE are associated with increase in life cycle GHG emissions savings across all the climate change scenarios considered compared with the baseline scenario. Thus, both WIBM & WIBE would be positively affected by simultaneous changes in *T*, *P*, and *[CO₂]*. Compared with the baseline period, the predicted increase ranges from +0.1 to +37.8% for WIBM, and +1.0 to +34.4% for WIBE.

As shown in Figures 4.8 and 4.9, life cycle GHG emissions savings of WIBM & WIBE would increase with increase in *T*. For instance, under (T = 0.5 ^oC; P = +10%; $[CO_2]$ = 400 ppm) scenario, WIBM was predicted to incur a +2.1% increase compared with the baseline period. Also under (T = 1.5 ^oC; P = +10%; $[CO_2]$ = 400 ppm), (T = 3.5 ^oC; P = +10%; $[CO_2]$ = 400 ppm), and (T = 4.5 ^oC; P = +10%; $[CO_2]$ = 400 ppm) scenario, model prediction showed that WIBM would incur a +7.3%, +25.3%, and +29.5% increase respectively, compared with the baseline scenario. Compared to WIBM, similar trend was also exhibited by WIBE in response to increasing *T*. Moreover, scenarios of increasing $[CO_2]$ have been shown to have positive impact on life cycle GHG emissions savings of both WIBM & WIBE. For example, under ($[CO_2]$ = 400; T = 0.5 ^oC; P = -20%), ($[CO_2]$ = 540; T = 0.5 ^oC; P = -

20%), and ($[CO_2]$ = 680; T = 0.5 ^oC; P = -20%) scenarios, a +9.4%, +14.1%, and +17.8% increase was predicted for WIBE.

In addition, decreased in P coupled with increased $[CO_2]$ have been shown to have positive impact on life cycle GHG emissions savings of both WIBE & WIBM. For instance, a +10.4% increase was recorded for WIBM under (P = -20%; T = 0.5 ^oC; $[CO_2]$ = 540 ppm) scenario and a +2.3% increase was incurred under (P = +20%; T = 0.5 ^oC; $[CO_2]$ = 540 ppm) scenario.

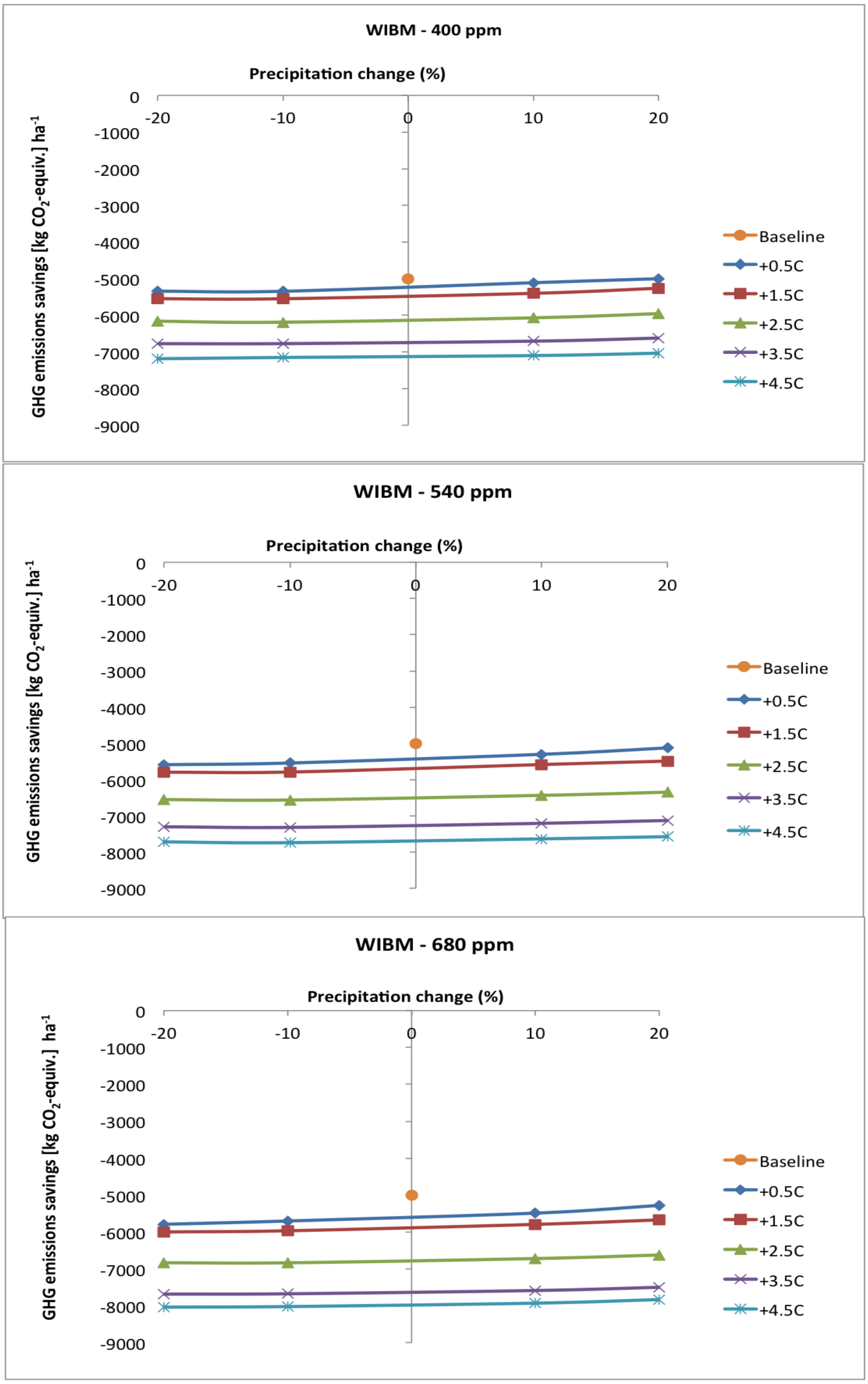

Figure 4.8: Calculated life cycle GHG emissions savings of WIBM (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of WIBM from the 1981 - 1990 baseline scenario is also shown.

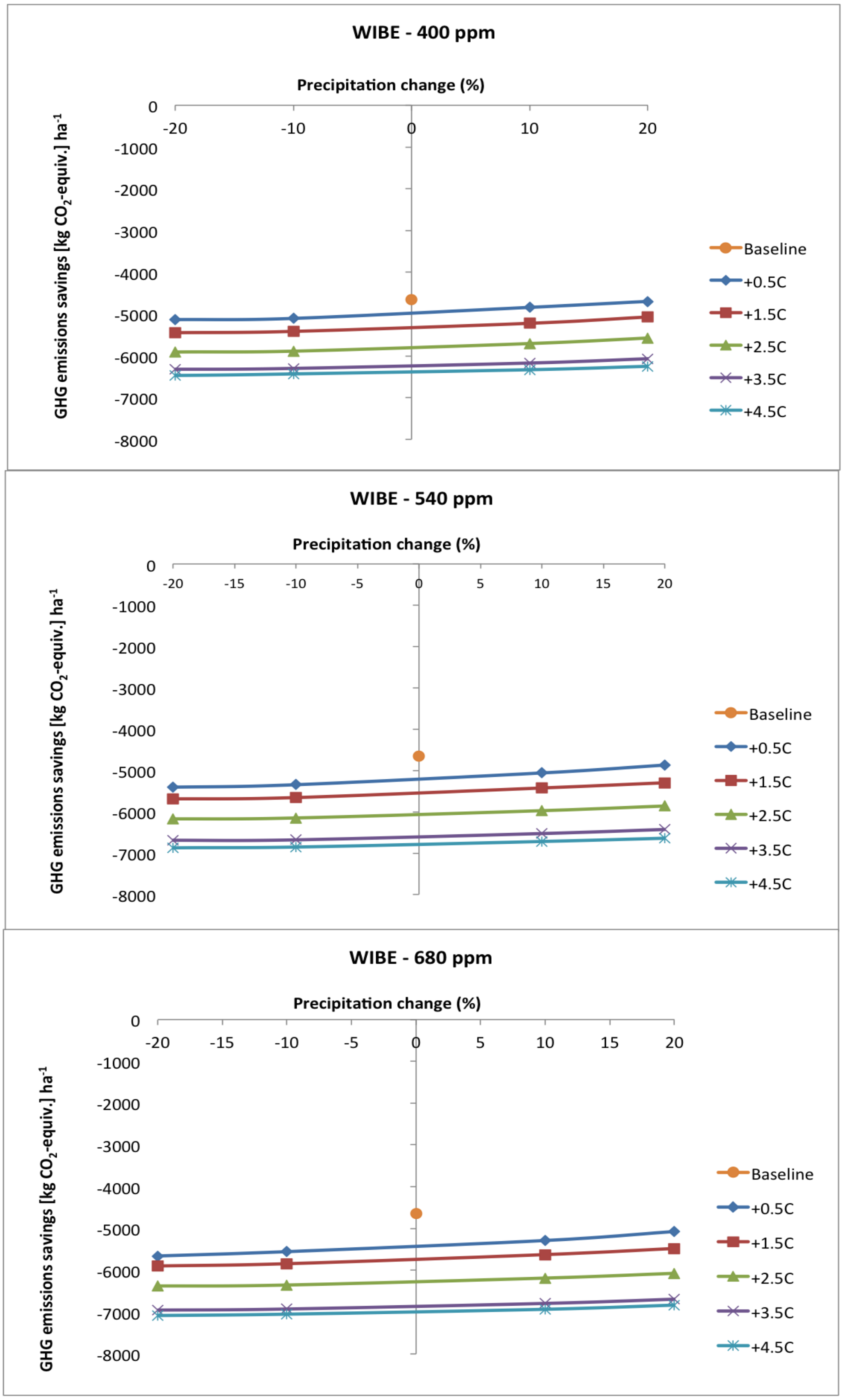

Figure 4.9: Calculated life cycle GHG emissions savings of WIBE (kg CO_2-equiv. ha^{-1}) from scenarios of future climate projections based on simultaneous changes in *T*, *P*, and *[CO_2]*. The calculated life cycle GHG emissions savings of WIBE from the 1981 - 1990 baseline scenario is also shown.

4.5 Summary

Investigations on the potential impact of climate change on corn, soybean, and wheat showed that changing *T*, *P*, and *[CO_2]* would have substantial effect on the yields and their life cycle GHG emissions savings. It was also revealed that for the chosen climate change scenarios and crop, corn feedstock yields as well as life cycle GHG emissions savings of CBE, CBM, and CIBE would be negatively affected by climate change. By comparison, soybean yields and life cycle GHG emissions savings of SBD, SIBM, and SIBE would be both positively, as well as negatively affected by the predicted changes in *T*, *P*, and *[CO_2]* in this analysis. In contrast, wheat yields would be positively affected by changing *T*, *P*, and *[CO_2]* across all the chosen climate change scenarios. Results also showed that increased *T* had the most significant impact on energy crop yields, though the degree of the impact varied with the type of crop. Corn, soybean, and wheat responded differently to changing *T*, *P*, and *[CO_2]*.

Overall, results suggest that combined changes in *T*, *P*, and *[CO_2]* could have substantial impact on energy crop yields as feedstock for biofuels and the resulting life cycle GHG emissions savings from these biofuels when they are used as alternatives to conventional fossil fuels.

CHAPTER 5: OVERAL DISCUSSIONS

5.1 Introduction

Reducing anthropogenic GHG emissions globally is a key driver for the development of large-scale renewable biofuels [252, 253]. The cereals: corn, soybean, and wheat are being promoted by many governments such as the EU and USA, as potential biofuel feedstock sources and possible replacements of fossil fuels such as gasoline and diesel due to the environmental benefits derived from their production and utilization [13, 152, 254-256]. It has been acknowledged that LCA as a decision support tool can yield valuable insights about potential environmental effects of biofuels production and can support robust strategic decision-making [257, 258]. Most LCA studies indicate significant life cycle GHG emissions benefits of using biofuels over conventional fossil fuels [259, 260].

Nonetheless, the net life cycle GHG emissions savings resulting from production and utilization of biofuels is being subjected to changes in the future due to projected changes in climatic conditions. However, assessment of the potential impacts of climate change on life cycle GHG emissions savings of biofuels from dedicated energy crops was not adequately addressed.

As previously reported (Chapter 4), the studies involves series of experiments designed in order to evaluate the impact of projected combined changes in *T*, *P*, and $[CO_2]$ on life cycle GHG emissions savings of corn, soybean, and wheat-based biofuels. This section is designed to present an overview of the results obtained with limitations of the research, and recommendations for future work.

5.2 The baseline scenario

Although biofuels at certain stages of their life cycle (e.g., farm operations, transportation, and processing) exhibits negative environmental impacts, production and utilization of biofuels as replacement for fossil fuels tended to be more environmentally beneficial when they are used as replacement for conventional fossil-based fuels.

Under the baseline (1981 – 1990) scenario, this analysis suggest that production and use of corn-based biofuels: CBE, CIBM, and CIBE could save -4743.32 kg CO_2-equiv. ha^{-1}, -8573.31 kg CO_2-equiv. ha^{-1}, and -10996.7 kg CO_2-equiv. ha^{-1} respectively, of the total life cycle GHG emissions of CO_2, CH_4, and N_2O for the production and utilization of an energetically equivalent amount of fossil gasoline and electricity, respectively. Similarly, soybean-based biofuels: SBD, SIBM, and SIBE could save -2655.41 kg CO_2-equiv. ha^{-1}, -3441.1 kg CO_2-equiv. ha^{-1}, and -1350.04 kg CO_2-equiv ha^{-1} respectively, of the total life cycle GHG emissions of CO_2, CH_4, and N_2O for the production and utilization of an energetically equivalent amount of fossil diesel, gasoline, and electricity, respectively. Findings from this thesis also suggest that wheat-based biofuels: WBE, WIBM, and WIBE could save -2776.1 kg CO_2-equiv. ha^{-1}, -500.87 kg CO_2-equiv. ha^{-1} and -4648.93 kg CO_2-equiv. ha^{-1} respectively, of the total life cycle GHG emissions of CO_2, CH_4, and N_2O of production and utilization of an energetically equivalent amount of fossil gasoline and electricity, respectively. Nonetheless, it is important to note that for greater sustainability we require a large negative value for the life cycle GHG emissions savings.

These results are in agreement with findings from studies conducted by [6, 97, 170, 261] that showed that production and use of biofuels would save the net life cycle GHG emissions of energetically equivalent amount of fossil fuel they displaced either totally or as a blending component of fuel engine [262]. For instance, according to [6] and Larson [97], life cycle GHG emissions savings of -4290 kg CO_2-eq ha^{-1} yr^{-1} and -4900 kg CO_2-eq ha^{-1} yr^{-1}, respectively could be achieved from corn when grown on marginal land in the US Midwest. In addition, result from [97] showed that life cycle GHG emissions savings of about -2100 kg CO_2-equiv. ha^{-1} yr^{-1} could be achieved from soybean biodiesel.

However, it is important to note that the net life cycle GHG emissions savings varies greatly across crops and production technologies. Among the three crops, corn provides higher benefits in terms of high net life cycle GHG emissions savings than wheat and soybean, probably due to higher total biomass yield per ha. Meanwhile, CIBE saves more life cycle GHG emissions than CIBM and CBE. On the other hand, WIBM saves more life cycle GHG emissions than WBE and WIBE. Similarly, SIBM saves far more life cycle GHG emissions than SIBE and SBD. In general, these findings suggest that production and utilization of second-generation biofuels could offer more net life cycle GHG emissions savings than conventional grain/seed based, first-generation biofuels.

5.3 The climate change scenarios

Under climate change scenarios, findings from this study showed that biofuels feedstock production and net life cycle GHG emissions savings are affected by climate change. Future production of biofuels feedstocks and production processes are likely to have lower and/or higher life cycle GHG emissions savings depending on the type of feedstock, as a result of reduction in yield due to climate change. Climatic factors such as *T*, *P*, and *[CO_2]* could determine the average yield response of bioenergy crops. Clearly, this study illustrates that biofuel feedstocks respond differently to changing climate based on their photosynthetic metabolic pathway (i.e. C3 and C4 pathways). Crop yields response was higher in C3 crops than C4 crops.

In future climate change scenarios, models prediction showed that energy crops productivity and net life cycle GHG emissions savings from corn-based biofuels: CBE, CIBM, and CIBE responded to changes in *T*, *P*, and *[CO_2]*. Moreover, changes in *T*, *P*, and *[CO_2]* expected at the end of the century could make corn-based biofuels production not environmentally sustainable. The net life cycle GHG emissions savings for CBE, CIBE, and CIBM decreased significantly under all projected climate change scenarios even with the direct effects of CO_2. Atmospheric air temperature, *T*, was shown to be the most relevant climatic factor, which has the highest effect on crops yield and net life cycle GHG emissions savings [119, 263]. However, increased atmospheric *[CO_2]* tended to reduce the combined effects of increased *T* and changing *P*.

Moreover, the effects of simultaneous changes in *T*, *P*, and *[CO_2]* on life cycle GHG emissions clearly pointed that there is a substantial effects of climate change on sustainability of corn-based biofuels. The negative effects of climate change on life cycle GHG emissions savings of corn-based biofuels relative to baseline scenario were mainly due to the decrease in corn grain and stover yields ha^{-1} that corresponded to the biofuel output used in lieu of a fossil fuel equivalent. Comparing baseline and future climate change scenarios, life cycle GHG emissions savings results of corn-based biofuels suggests that simultaneous changes in *T*, *P*, and *[CO_2]* could cause a reduction of between -4.2-46.1%, -2.6-37.7%, and -1.6-33.4% in net life cycle GHG emissions savings of CBE, CIBM, and CIBE respectively, in Gainesville, USA by the end of the 21st century. Studies conducted by [264] in the USA, which produces 41% of the world's corn and 38% of the world's soybeans showed that average corn yields would decrease by -30 to -46% before the end of the century under the slowest (B1) warming scenario and decrease by -63 to -82% under the most rapid warming scenario (A1FI).

Consequently, the predicted decline in net life cycle GHG emissions savings would have important impact on the environmental sustainability of corn-based biofuels and climate change mitigation goals aimed at reducing global GHG emissions for example, the *Renewable Fuel Standard* (RFS2) set by the US government, which set out the objective of an aggregate of 136.26 billion litres of renewable fuel to be used in transport, and also required producers of advanced and standard biofuels to reduce their life cycle GHG emissions by at least 50% and 20% respectively [92]. This situation could lead to land expansion (land use change) in order to close the yield gap and making producers more vulnerable to government policy changes [15, 72, 192, 265]. Also as the yield goes down, this would create more pressure on the feedstock supply leading to high-rise in feedstock price.

Furthermore, it is essential to adopt additional adaptation measures that will serve to reduce the negative impacts of projected climate change and variability on biofuel feedstocks productivity and net life cycle GHG emissions savings. According to [120], there are two primary approaches for adapting crops to climate change: (i) improving existing crop cultivars and developing new crops, and (ii) developing new cropping systems and methods for field crops management. These includes adjustment of planting dates and crop variety; crop relocation; improved land management e.g., erosion control and soil protection through tree planting [34]. Investigations conducted by [266] showed that a combination of early planting for spring – summer crops and the use of slower-maturing winter cereal cultivars could help in maintaining crop yields. Irrigation was also shown to be essential as a means to increase crop yields as well as to decrease inter-annual variability in crop yields due to climate change [41].

The effect of combined changes in on corn grain yield was in agreement with previous studies that demonstrated the effect of climate change on energy crop production (e.g., [16, 30-32, 41, 267-272]). Findings from [266] suggested that the decline in corn grain yield was as a result of combined effects of changing climate, specifically due to warmer air temperatures, which accelerated plant phenology, reducing dry matter accumulation and crop yields by -10 to -40%. Warmer air temperatures have been shown to reduce crop yields by making the crop to grow more quickly thereby reducing the amount of time that seeds have to grow and mature [23]. In a study conducted by [273], it was found that increased average temperatures of 1.7 ^{o}C could reduce the time to flowering of crops by 11 days leading to a decline in total biomass and grain yield. However, the effect of increased temperature on crop productivity will depend on the crop's optimal temperature for growth and reproduction: for temperatures lower than the optimum value, an increase in temperature will be positive for crop production; for temperatures higher than the optimum value an increase on temperature will be negative for crop production [272]. Findings from a study conducted by [264] suggested that crop yields increase with temperature of up to 29 °C for corn and 30 °C for soybeans grown in the USA, but that temperatures above these thresholds would be very harmful.

Investigations of the impact of climate change on soybean production and net life cycle GHG emissions of SBD, SIBM, and SIBE predicted contrasting results to that of corn-based biofuels. Soybean, being a C3 crop tended to be more sensitive to combined changes in *T*, *P*, and *[CO_2]*. This is in agreement with [23] who reported that C3 crops are generally more sensitive to changes in climatic factors such as temperature, rainfall, and elevated CO_2. Soybean-based biofuels are likely to experience both reduction and increase in feedstocks yields, and life cycle GHG emissions savings depending on changes in *T*, *P*, and *[CO_2]*. Model predictions suggests that combined changes in *T*, *P*, and *[CO_2]* projected at the end of the 21st century could cause -0.7 to -60.8%, -0.1 to -44.6%, and -0.1 to -82.6% reduction in net life cycle GHG emissions savings of SBD, SIBM, and SIBE respectively. And on the other hand, climate change could also cause an increase in net life cycle GHG emissions savings of +0.22 to +27%, +0.1 to +28%, and +0.1 to +31.6% for SBD, SIBM, and SIBE respectively. These expected changes could make soybean-based biofuels not environmentally sustainable as well as more environmentally sustainable depending on climate change scenario, compared with the baseline period. Based on the simulated results, highest reductions in net life cycle GHG emissions are expected when *[CO_2]* = 400; *P* = -20%; and *T* = +5 ^{o}C, and lowest reductions when *[CO_2]* = 680; *P* = -5%; and *T* = +3.5 ^{o}C. Whilst highest increases in net life cycle GHG emissions savings are expected when *[CO_2]* = 680; *P* = +20%; and *T* = +1.5 ^{o}C and lowest increases when *[CO_2]* = 540; *P* = +10%; and *T* = +3.5 ^{o}C.

Clearly, as shown in the previous section (chapter 4) it appears that the scenarios of increasing *[CO_2]* and *P* will have a positive impact on life cycle GHG emissions savings of soybean-based biofuels. The decrease in net GHG emissions savings per ha for soybean-based biofuels was mainly driven by increased air *T*, which caused significant decrease in the harvestable grain/seed and biomass yields of soybean. Furthermore, as the atmospheric *[CO_2]* increases coupled with warming (increased *T* of up to +4.5 ^{o}C) the life cycle GHG emissions savings for soybean-based biofuels improve even higher than that of the current baseline scenario. Also the potential GHG emissions savings gap between CBE and SBD per ha rapidly closes with increasing *[CO_2]*. This demonstrated that SBD production would be similar, if not better, in a warmer (at *T* not above +4.5 ^{o}C) and CO_2 enriched future. This might not be unconnected with the photosynthetic advantage that soybean (a typical C3 crop) has over corn (a typical C4 crop) at considerably high *T* and elevated atmospheric *[CO_2]* than today's condition (400 ppm) [274]. It has been revealed that at elevated CO_2, stimulation of photosynthesis is the driving force for increased growth and yield of C3 crops [32, 126, 194, 275-278]. Therefore, a dangerous combination for climate change would be increased warming without increased atmospheric level of CO_2. According to [274] "*We should be less concerned about rising CO_2 and rising temperatures and more worried about the possibility that future CO_2 will suddenly stop increasing*". This work therefore, argues that even with increasing atmospheric levels of *[CO_2]*, rising temperature is of great concern. Overall, *T* appeared to have a relatively higher impact as compared to *P* and *[CO_2]* changes.

Model results as presented in the previous section (chapter 4) shows that in future climate change scenarios, wheat productivity and net life cycle GHG emissions savings of wheat-based biofuels: WBE, WIBM and WIBE responded to changes in *T*, *P*, and *[CO_2]*. Nevertheless, the expected changes in *T*, *P*, and *[CO_2]* at the end of the

21st century could make wheat-based biofuels production more environmentally sustainable relative to the baseline condition. Under all future climate change scenarios, net GHG emissions savings for WBE, WIBM, and WIBE increased significantly. This was in agreement with findings from [279, 280].

As in the case of corn and soybean, atmospheric air temperature was also shown to be the most relevant climatic factor on wheat yields [119, 263]. In comparison with corn-based and soybean-based biofuels, wheat-based biofuels would have a more positive response to increasing *T* coupled with elevated *[CO2]*. Thus, contrary to corn and soybean increased *T* and *[CO2]* coupled with decreased *P* increased wheat yields and the resulting net life cycle GHG emissions savings. In a study by [284], elevated CO_2 concentration and increased air temperature (up to 3 ^oC) have been found to increase wheat yields, particularly at sufficient nitrogen fertilization and relatively dry conditions. In a study conducted by [273] using Free Air Carbon dioxide Enrichment (FACE) experiment, largest increase in wheat yield was found to occur with elevated atmospheric CO_2 concentration in dry and high nitrogen treatments, whereas little or o response was observed in wet and low nitrogen supply treatments.

The positive response to the temperature and CO_2 increase is likely due to the unique photosynthetic ability of C3 crops. A study of the impact of increased temperature and CO_2 on C3 crops predicted a generally increasing trend in net photosynthesis with warmer temperatures and elevated CO_2 until optimum temperature is reached [281]. In another study [32] both photosynthetic rate and optimum temperature has been found to be higher at elevated atmospheric CO_2 concentration because, increasing atmospheric CO_2 concentration stimulates both net photosynthetic carbon assimilation and biomass production for C3 crops. It was also revealed that at elevated CO_2 concentration the optimum temperature and net photosynthesis of C3 crops tend to increase by +5 ^oC and +42% respectively, compared to lower CO_2 levels [281]. However, regardless of CO_2 level, photosynthesis gradually decreased at temperatures higher than the optimum temperature since increase in temperature reduces crops photosynthetic efficiency and stimulates photorespiration [282, 283]. There have been reports that changes in atmospheric CO_2 levels might play a key role in nutrients and water uses, such as evapotranspiration, which in turn indirectly affect net photosynthesis and yield, especially under water deficit conditions [17, 276]. It was also revealed that elevated CO_2 and increased temperatures reduces evapotranspiration with ample nitrogen fertilizer [273]. Thus, elevated CO_2 and increased temperature are expected to have positive impact on wheat grain yield in future climate change conditions.

Similar to soybean, wheat response to atmospheric $[CO_2]$ was higher than that of corn due to their photosynthetic difference. Soybean and wheat being C3 crops have been shown to have a better photosynthetic advantage than corn (C4 crop) at elevated CO_2 concentrations with increasing temperature [126, 188, 202, 224, 274, 282]. The effects of combined changes in *T*, *P*, and $[CO_2]$ on life cycle GHG emissions clearly demonstrated that there is also a substantial effects of climate change on sustainability of wheat-based biofuels.

The positive effects of changing *T*, *P*, and $[CO_2]$ on life cycle GHG emissions savings of wheat-based biofuels relative to baseline scenario were mainly due to the increase in wheat grain and straw yields that corresponded to the biofuel output used in lieu of a fossil fuel equivalent. Comparing baseline and future climate change scenarios, life cycle GHG emissions savings results of wheat-based biofuels suggests that simultaneous changes in *T*, *P*, and *[CO_2]* could cause an increase of between +2.5 to +33.5%, +0.1 to +37.8%, and +1.0 to +34.4% in net life cycle GHG emissions savings of WBE, WIBM, and WIBE respectively. The predicted increase in net life cycle GHG emissions savings would have important impacts on the environmental sustainability of wheat-based biofuels and climate change mitigation goals aimed at reducing global GHG emissions. For example, in meeting the European Directive (*EU Directive 2009/28/EC*) on the promotion of the use of biofuels or other renewable fuels for transport within the EU, which sets out the objective of 10% for biofuels in transport and also a minimum 35% reduction in GHG emissions to be achieved by biofuels during their life cycle by 2020 and 80% by 2050 below the 1990 baseline [81].

In general, simultaneous changes in *T*, *P*, and *[CO_2]* would have substantial impact on energy crop productivity and net life cycle GHG emissions savings. Increasing atmospheric levels of *[CO_2]* would benefit bioenergy crops production due to the aerial fertilization effect. CO_2 being an aerial fertilizer would enhance plant growth and development considering the fact that it is the primary raw material used by crops in the synthesis of organic matter *via* photosynthesis. The more CO_2 there is in the atmosphere, the better crops can perform this vital function even under stressed conditions because CO_2 sequestration ability of the crop rises along with atmospheric CO_2 concentration [125, 285]. Atmospheric CO_2 concentration of 475-600 ppm has been shown to increase leaf photosynthetic rates of crops by +40% [269, 283]. According to [278] elevated CO_2 decreases stomatal conductance of water by an average of -22%, which decreases overall water use by the crop. However, the magnitude of the overall effect will depend on other determinants such as air temperature and plant size [282]. A review of existing knowledge by [286] on interactive influences of atmospheric CO_2 concentration, temperature and soil moisture on crop growth, development and yield as well as on plant water use efficiency (WUE), and uptake efficiencies of soil-immobile nutrients revealed that elevated atmospheric CO_2 would increase leaf and canopy photosynthesis, especially in C3 crops. It was also found that elevated CO_2 would increase biomass yield, reduce transpiration of most crop and improve WUE [286].

5.3 Conclusion

A robust methodology that integrates climate change projection and cropping system modelling coupled to life cycle assessment modelling for assessing the impact of changing climate on life cycle GHG emissions savings of biofuels has been developed. CSM models linked to LCA models were found to be suitable for investigating the impact of future climate on productivity and environmental sustainability of biofuels from dedicated energy crops: corn, soybean and wheat.

As is shown in this thesis, the potential impacts of climate change on energy crops productivity and net life cycle GHG emissions savings could be very large and diverse, and that the anticipated life cycle GHG emissions reductions of biofuels would not be the same in the future. However, policy makers do not consider climate change when designing policies for the promotion of large-scale biofuels production.

By the end of the 21st century, climate change could have negative effects on the environmental sustainability of corn-based biofuels. In contrast, climate change is expected to have both benefits and drawbacks on the environmental sustainability of soybean-based biofuels depending on climate change scenario. Furthermore, future climatic conditions are expected to have beneficial effects on the environmental sustainability of wheat-based biofuels.

Temperature will have a more devastating effect on the GHG emissions reductions for all the crops and technologies considered. Apparently, the GHG emissions savings will continue to decline with rising air temperature. For corn, even an increase of 1.5 ^{o}C will have a significant negative effect on life cycle GHG emissions savings for all the technologies considered. The highest impact will be when the air temperature rises by up to 5 ^{o}C. However, the life cycle GHG emissions savings of soybean-based and wheat-based biofuels will be affected positively by a temperature increase of up to 4.5 ^{o}C depending on future climate scenario. Nevertheless, direct effect of increasing levels of atmospheric CO_2 has been projected to minimize the severe impact of these increasing temperatures.

'Multi – output' or 'integrated' system as used in this thesis for combined production of biofuel and bioelectricity could be a promising option for sustainable bioenergy production system and the potential life cycle GHG emissions savings are directly proportional to the energy crop's dry biomass yield per ha. As the yield increases, the resulting life cycle GHG emissions savings from its production also increases considerably, and vice versa. It is also worth noting that the relationship between direct and indirect energy inputs due to energy crop cultivation and yield per unit land is non – linear since all inputs are done on per unit land basis not per yield. High yield could be attained for instance; per ha with very small energy input and a very low yield could also be obtained with very high energy input per ha.

While it is widely anticipated that biofuels would play a key role in achieving the IPCC's target of 50 – 80% reduction in global GHG emissions through renewable options by 2050, this thesis suggests that the potential GHG emissions reductions from biofuels will be affected by climate change. Thus, the life cycle GHG emissions savings of biofuels cannot be taken for granted. Policy measures are therefore required for the deployment and expansion of bioenergy systems from dedicated energy crops in the face of a changing climate. This will significantly require some strategies for improving the productivity of existing energy crops and an understanding of the complex relationship between energy crops and the environment. High yielding and climate change resilient energy crops are therefore required for the deployment of large-scale bioenergy system. But care must also be taken in choosing which energy crop to grow in a changing climate. Crops like wheat and soybean (C3 crops) that thrives well in warmer climates have an edge over corn (C4 crop). Checks should also be conducted on this present work either by using real field test or simulations study. Findings from this research should also be taken into account by policy makers in designing an action plan for the deployment of large-scale bioenergy system. Care should also be taken in choosing the best value crop (crop with the most benefit) which offers more energy and GHG balance per unit mass (kg) of the crop. This can be identified by either taking into account the grain/seed or total biomass yield per ha (when whole crop is considered) or usage in terms of high calorific value per unit mass (kg).

5.4 Research limitations

By reflecting on the research process, it is easy to see where improvements could be made. Although the methodological approach was carefully considered and the tools used were carefully selected, given the complex nature of CSM and LCA studies, there are a number of points regarding the research. The use of CSM and LCA models as robust and efficient tools for informing or making policy decisions requires extensive data gathering. Uncertainty and variability are inherent in the LCA of biofuels, especially in the assessment of new technologies. In each of the tools applied in this research, data availability and quality has always been the limiting factors for complete environmental effects assessment.

5.5 Recommendations for future research work

This modeling approach can also be applied for investigating the impact of climate change on productivity and net GHG emissions reductions potential of different energy crops, biofuels technologies, and different regions of the world. Studies should be carried out to assess the impact of individual changes in *T*, *P*, and $[CO_2]$ on the carbon footprint of biofuels in order to investigate whether or not the result will agree well with that of simultaneous (combined) change. More research is also required under field conditions to better understand the feedback between changes in *P*, *T*, and the magnitude of the CO_2 fertilization effect on energy crops yield. Better understanding of the underlying mechanisms of potential changes in crop tolerance to stress under elevated CO_2 is particularly important.

Further research on the impact of extreme weather events such as drought, flood, and wind on energy crops productivity and on crops adaptation to changing climate is also required for decision makers to develop effective strategies and policies to tackle future climate change impacts and its consequences on biofuels production.

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Appendices

Appendix A: Corn bioethanol (CBE) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario: = -4743.31678 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	**-20**	-4168.8	-4033.8	-3819.3	-3545.3	-3321.7	-3006.1	-2732.1	-2557.7
	-15	-4217.9	-4078.2	-3891.6	-3634.8	-3410.3	-3090.9	-2786.6	-2635.6
	-10	-4243.8	-4122.7	-3944.5	-3707.4	-3500.7	-3161.3	-2854.4	-2677.0
	-5	-4255.6	-4162.3	-3974.7	-3747.6	-3559.2	-3256.2	-2916.4	-2720.4
	5	-4291.1	-4189.2	-4013.2	-3799.8	-3614.4	-3332.7	-3004.0	-2798.3
	10	-4306.1	-4200.2	-4024.7	-3815.3	-3642.0	-3355.7	-3044.3	-2845.4
	15	-4309.74	-4208.78	-4045.27	-3825.01	-3659.49	-3379	-3052.76	-2873.96
	20	-4311.47	-4213.14	-4052.3	-3843.67	-3670.07	-3405.08	-3080.85	-2892.01
470	**-20**	-4249.97	-4128.85	-3934.37	-3658.54	-3435.65	-3141.67	-2840.87	-2674.09
	-15	-4290.99	-4173.37	-3985.07	-3771.31	-3539.12	-3203.08	-2899.39	-2733.54
	-10	-4308.08	-4210.37	-4021.39	-3821.55	-3630.67	-3293.43	-2963.44	-2779.92
	-5	-4324.2	-4232.29	-4064.79	-3852.75	-3677.62	-3380.87	-3032.77	-2836.93
	5	-4344.14	-4264.62	-4094.4	-3898.44	-3714.18	-3436.99	-3121.54	-2911.61
	10	-4349.21	-4278.28	-4108.26	-3907.62	-3736.01	-3466.5	-3141.63	-2958.87
	15	-4351.23	-4283.54	-4114.94	-3920.01	-3748	-3487.47	-3158.06	-2979
	20	-4353.28	-4286.1	-4119.17	-3930.32	-3757.02	-3506.49	-3182.12	-3009.53
540	**-20**	-4338.51	-4216.02	-4033.66	-3801.84	-3580.49	-3252.4	-2942.24	-2786.54
	-15	-4355.5	-4255.7	-4068.61	-3876.47	-3670.5	-3334.77	-3025.94	-2847.88
	-10	-4368.02	-4286.1	-4118.41	-3914.38	-3736.24	-3433.64	-3093.98	-2895.69
	-5	-4382.43	-4298.83	-4134.37	-3953.59	-3768.64	-3483.06	-3165.03	-2947.96
	5	-4408.14	-4319.35	-4166.25	-3987.74	-3808.75	-3539.6	-3224.79	-3017.9
	10	-4415.02	-4325.52	-4173.48	-3998.11	-3822	-3561.47	-3249.72	-3050.74
	15	-4417.28	-4328.09	-4186.06	-4002.64	-3831.14	-3578.1	-3269.37	-3070.55
	20	-4413.4	-4337.61	-4178.91	-4014.08	-3846.3	-3589.57	-3289.16	-3096.18
610	**-20**	-4425.88	-4311	-4142.14	-3954.51	-3747.32	-3393.56	-3074.87	-2902.37
	-15	-4435.23	-4341.81	-4168.64	-3992.92	-3824.67	-3491.09	-3155.4	-2965.57
	-10	-4448.49	-4360.66	-4200.6	-4019.83	-3861.3	-3571.03	-3225.6	-3030.81
	-5	-4460.14	-4382.4	-4214.97	-4047.37	-3893.13	-3603.35	-3283.39	-3089.64
	5	-4478.92	-4404.2	-4240.98	-4068.79	-3919.46	-3656.34	-3340.55	-3151.76
	10	-4477.16	-4407.43	-4247.96	-4079.46	-3924.62	-3671.63	-3368.07	-3176.84
	15	-4480.22	-4409.9	-4258.58	-4084.49	-3938.53	-3685.83	-3384.1	-3197.9
	20	-4480.8	-4412.85	-4260.54	-4087.56	-3950.19	-3697.69	-3397.34	-3224
680	**-20**	-4490.7	-4411.7	-4233.33	-4061.1	-3901.99	-3543.23	-3216.78	-3022.75
	-15	-4496.47	-4434.71	-4269.62	-4083.06	-3935.06	-3634.81	-3295.36	-3093.33
	-10	-4509.49	-4456.34	-4290.81	-4115.19	-3966.43	-3683.54	-3373.02	-3162.5
	-5	-4511	-4467.41	-4310.29	-4125.08	-3994.72	-3708.5	-3395.92	-3210.94
	5	-4524.56	-4479.35	-4324.73	-4146.69	-4019.68	-3758.94	-3453.49	-3273.81
	10	-4527.19	-4487.97	-4327.13	-4158.26	-4028.48	-3773.37	-3469.71	-3297.63
	15	-4529.75	-4486.06	-4335.56	-4161.15	-4038.25	-3794.65	-3483.83	-3316.68
	20	-4542.32	-4498.79	-4337.98	-4162.5	-4042.65	-3807.98	-3497.56	-3333.06

Appendix B: Soybean biodiesel (SBD) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -2655.41 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	**-20**	-2237.87	-2102.59	-1929.26	-1783.02	-1541.1	-1345.46	-1124.98	-890.852
	-15	-2371.53	-2233.95	-2052.06	-1887.94	-1675.96	-1443.8	-1221	-960.998
	-10	-2465.24	-2321.72	-2152.33	-1996.26	-1771.07	-1550.04	-1287.32	-1039.83
	-5	-2567.28	-2429.98	-2261.84	-2083.74	-1866.75	-1638.08	-1396.82	-1098.82
	5	-2689.69	-2555.99	-2428.93	-2274.54	-2048.07	-1817.45	-1540.43	-1216.39
	10	-2719.41	-2603.73	-2485.68	-2324.96	-2117.83	-1872.88	-1590.67	-1259.62
	15	-2738.02	-2629.65	-2515.56	-2368.69	-2181.21	-1934.93	-1651.81	-1313.21
	20	-2754.27	-2650.5	-2551.82	-2392.16	-2203.84	-1969.85	-1684.29	-1357.33
470	**-20**	-2558.9	-2418.38	-2256.96	-2071.52	-1816.82	-1594.46	-1355.06	-1093.94
	-15	-2698.14	-2554.23	-2366.29	-2196.24	-1946.81	-1709.04	-1465.09	-1190.87
	-10	-2800.59	-2647.17	-2478.16	-2293.58	-2070.79	-1820.79	-1549.9	-1259.05
	-5	-2916.34	-2764.41	-2594.05	-2398.45	-2184.53	-1925.96	-1650.29	-1328.94
	5	-3031.51	-2902.7	-2771.37	-2594.45	-2354.5	-2108.52	-1804.98	-1458.83
	10	-3057.17	-2938.74	-2819.28	-2660.19	-2428.72	-2161.64	-1863.23	-1497.28
	15	-3083.63	-2959.31	-2854.85	-2692.44	-2491.62	-2226.12	-1912.02	-1554.54
	20	-3095.22	-2985.11	-2881	-2723.15	-2521.94	-2264.05	-1957.98	-1599.19
540	**-20**	-2796.31	-2636.56	-2483.27	-2294.79	-2012.59	-1783.79	-1518.07	-1240.52
	-15	-2931.62	-2791.42	-2584.58	-2397.75	-2157.31	-1895.02	-1633.22	-1349.93
	-10	-3060.04	-2902.14	-2723.33	-2511.37	-2273.63	-2013.61	-1731.7	-1436.74
	-5	-3166.45	-3008.71	-2825.61	-2625.7	-2398.46	-2123.56	-1841.72	-1494.25
	5	-3279.15	-3148.98	-3012.68	-2829.36	-2577.64	-2324.94	-2002.51	-1636.67
	10	-3303.05	-3180.02	-3057.51	-2891.95	-2664.46	-2374.56	-2053.68	-1667.5
	15	-3328.66	-3215.37	-3094.25	-2925.66	-2719.37	-2447.28	-2112.73	-1728.25
	20	-3341.48	-3232.03	-3122.35	-2961.48	-2747.18	-2478.11	-2159.14	-1770.59
610	**-20**	-2963.17	-2795.4	-2655.2	-2448.09	-2169.05	-1910.07	-1641.51	-1348.56
	-15	-3105.54	-2959.76	-2744.94	-2568.05	-2298.94	-2032.11	-1756.95	-1462.61
	-10	-3234.31	-3072.77	-2886.66	-2684.48	-2424.74	-2151.32	-1858.72	-1551.27
	-5	-3343.84	-3190.91	-2999.85	-2795.25	-2552.39	-2274.32	-1973.22	-1610.07
	5	-3455.16	-3322.42	-3180.99	-2996.64	-2736.57	-2472.76	-2134.71	-1758.11
	10	-3479.49	-3354.17	-3226.49	-3056.37	-2825.43	-2524.06	-2188.72	-1792.49
	15	-3508.9	-3384.19	-3261.44	-3092.98	-2877.35	-2591.16	-2252.72	-1847.69
	20	-3519.43	-3400.58	-3291.74	-3128.47	-2908.41	-2629.37	-2300.97	-1889.5
680	**-20**	-3084.4	-2908.2	-2768.88	-2561.54	-2265.49	-2015.06	-1726.03	-1429.93
	-15	-3228.02	-3069.63	-2863.03	-2685	-2412.56	-2126.61	-1847.57	-1544.7
	-10	-3361.06	-3194.38	-3005.51	-2802.04	-2532.63	-2253.57	-1961.04	-1635.66
	-5	-3468.37	-3313.2	-3123.22	-2912.15	-2661.31	-2377.59	-2063.73	-1701.1
	5	-3582.62	-3432.35	-3302.36	-3113.53	-2852.86	-2577.73	-2237.12	-1845.18
	10	-3606.8	-3475.82	-3346.9	-3175.28	-2939.15	-2633.07	-2289.9	-1888.84
	15	-3633.36	-3506.8	-3393.52	-3209.23	-2990.36	-2706.37	-2352.08	-1948.68
	20	-3648.92	-3522.65	-3415.53	-3249.5	-3021.62	-2736.64	-2396.54	-1982.96

Appendix C: Wheat bioethanol (WBE) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -2776.10 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (°C)				
		0.5	1.5	2.5	3.5	4.5
400	-20	-3230.12	-3535.45	-3748.59	-3926.50	-3838.69
	-10	-3187.63	-3490.61	-3711.495	-3884.91	-3800.92
	10	-2974.04	-3317.44	-3534.34	-3747.63	-3693.25
	20	-2846.26	-3197.86	-3425.66	-3657.94	-3621.53
540	-20	-3458.56	-3719.31	-3867.33	-4076.76	-4013.19
	-10	-3394.13	-3664.56	-3818.13	-4036.88	-3982.69
	10	-3155.21	-3477.45	-3656.01	-3897.46	-3863.76
	20	-3007.82	-3364.11	-3555.26	-3810.47	-3793.56
680	-20	-3665.03	-3865.88	-3957.50	-4172.50	-4095.60
	-10	-3579.40	-3805.09	-3913.19	-4133.83	-4061.05
	10	-3347.49	-3614.77	-3755.95	-4004.30	-3958.15
	20	-3188.02	-3491.66	-3660.09	-3921.47	-3884.02

Appendix D: Corn integrated biomethanol (CIBM) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -8573.31 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	-20	-7757.22	-7552.03	-7258.05	-6863.69	-6528.86	-6055.64	-5660.51	-5342.91
	-15	-7827.35	-7621.97	-7365.27	-6996.64	-6659.32	-6186.04	-5750.1	-5460.59
	-10	-7869.06	-7685.31	-7445.76	-7109.87	-6796.14	-6288.48	-5855.03	-5530.34
	-5	-7888.24	-7743.39	-7485.86	-7170.35	-6886.81	-6430.34	-5947.08	-5601.4
	5	-7950.71	-7794.36	-7550.55	-7248.62	-6970	-6547.73	-6087.61	-5725.96
	10	-7976.14	-7818.06	-7575.83	-7277.13	-7011.39	-6585.94	-6142.16	-5790.42
	15	-7982.89	-7834.12	-7611.83	-7299.87	-7044.56	-6623.69	-6162.45	-5834.37
	20	-7986.54	-7842.61	-7628.15	-7333.95	-7069.56	-6661.86	-6205.01	-5863.93
470	-20	-7886.11	-7702.98	-7436.1	-7045.05	-6713.49	-6274.27	-5839.11	-5526.77
	-15	-7944.54	-7770.92	-7511.25	-7210.02	-6863.07	-6367.63	-5933.09	-5623.64
	-10	-7972.88	-7821.89	-7568.12	-7285.91	-7000.42	-6503.28	-6033.41	-5698.85
	-5	-8000.16	-7856.21	-7629.74	-7329.27	-7070.84	-6633.5	-6140.14	-5788.85
	5	-8040.09	-7915.8	-7682.07	-7402.15	-7132.83	-6713.16	-6273.18	-5904.54
	10	-8050.16	-7940.14	-7710.75	-7425.11	-7164.47	-6759.98	-6304.2	-5970.02
	15	-8053.6	-7950.74	-7726.22	-7451.15	-7190.47	-6789.09	-6335.35	-6003.74
	20	-8057.48	-7954.68	-7734.8	-7471.74	-7212.53	-6824.27	-6371.24	-6053.97
540	-20	-8020.84	-7841.19	-7590.36	-7266.71	-6935.78	-6453.9	-6015.75	-5711.11
	-15	-8048.88	-7895.49	-7647.12	-7374.04	-7067.21	-6576.02	-6138.63	-5806.45
	-10	-8069.63	-7941.25	-7716.25	-7432.37	-7165.71	-6722.25	-6243.54	-5888.28
	-5	-8097.46	-7963.81	-7742.86	-7487.41	-7213.91	-6794.05	-6353.42	-5969.78
	5	-8139.01	-8007.74	-7800.57	-7545.37	-7278.82	-6876.59	-6439.82	-6078.74
	10	-8149.27	-8019.53	-7817.56	-7569.09	-7306.25	-6905.24	-6482.38	-6125.71
	15	-8153.45	-8023.5	-7837.44	-7582.71	-7328.04	-6936.24	-6508.99	-6162.43
	20	-8150.07	-8037.75	-7829.38	-7600.68	-7355.54	-6960.61	-6545.49	-6202.2
610	-20	-8155.05	-7985.13	-7761.64	-7497.19	-7190.73	-6677.74	-6232.98	-5909.02
	-15	-8171.3	-8030.22	-7803.44	-7554.04	-7305.88	-6817.48	-6352.33	-6004.87
	-10	-8194.55	-8059.38	-7847.32	-7595.01	-7361.53	-6930.83	-6461.53	-6109.11
	-5	-8217.51	-8099.03	-7871.66	-7639.83	-7405.73	-6976.85	-6543.28	-6199.45
	5	-8246.21	-8135.28	-7921.9	-7681.81	-7454	-7053.85	-6629.96	-6294.96
	10	-8245.71	-8140.68	-7935.67	-7703.35	-7471.35	-7079.03	-6667.11	-6337.22
	15	-8251.73	-8145.88	-7950.2	-7712.9	-7496.81	-7107.14	-6695.46	-6369.16
	20	-8253.32	-8152.77	-7954.35	-7718.98	-7515.56	-7132.21	-6722.71	-6408.06
680	-20	-8256.29	-8136.84	-7903.94	-7658.07	-7426.44	-6904.39	-6456.87	-6108.56
	-15	-8267.43	-8169.91	-7953.11	-7697.41	-7474.62	-7034.73	-6574.17	-6216.54
	-10	-8292.52	-8204.79	-7985.88	-7744.63	-7521	-7102.76	-6689.26	-6321.24
	-5	-8298.15	-8227.16	-8021.2	-7762.93	-7562.87	-7137.61	-6723.47	-6396.15
	5	-8320.13	-8246.41	-8049.09	-7808.39	-7611.27	-7212.66	-6809.68	-6490.07
	10	-8324.59	-8260.2	-8053.18	-7828.08	-7631.81	-7238.91	-6831.49	-6527.61
	15	-8328.77	-8259.8	-8066.13	-7833.63	-7650.16	-7276.24	-6859	-6555.23
	20	-8346.22	-8277.72	-8072.16	-7836.47	-7656.99	-7298.82	-6886.36	-6586.07

Appendix E: Soybean integrated biomethanol (SIBM) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -3441.1 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (^oC)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	-20	-3159.1	-3046.68	-2907.66	-2781.93	-2567.14	-2372.43	-2145.93	-1907.81
	-15	-3284.94	-3173.04	-3031.04	-2894.56	-2708.92	-2488.45	-2268.6	-2013.67
	-10	-3378.39	-3264.29	-3135.45	-3000.99	-2812.34	-2605.33	-2355.17	-2129.8
	-5	-3479.23	-3369.64	-3241.9	-3095.57	-2915.22	-2707.59	-2481.1	-2203.71
	5	-3597.66	-3497.92	-3412.29	-3293.17	-3110.05	-2911.96	-2661.41	-2372.17
	10	-3630.71	-3545.44	-3465.75	-3350.74	-3186.33	-2975.01	-2724.46	-2434.65
	15	-3646.72	-3572.04	-3499.46	-3398.28	-3254.39	-3050.1	-2799.26	-2506.33
	20	-3662.68	-3592.08	-3533.18	-3421.69	-3281.15	-3093.92	-2850.65	-2569.6
470	-20	-3569.72	-3455.73	-3325.75	-3167.26	-2944.73	-2728.34	-2481.45	-2224.49
	-15	-3700.52	-3584.04	-3437.68	-3298.51	-3082.18	-2857.75	-2624.25	-2360.8
	-10	-3805.32	-3681.42	-3549.82	-3400.82	-3211.22	-2981.58	-2725.18	-2462.86
	-5	-3915.78	-3796.78	-3667.07	-3512.38	-3330.15	-3100.59	-2842.51	-2549
	5	-4027.26	-3933.92	-3848.08	-3709.98	-3515.41	-3307.78	-3035.22	-2733.54
	10	-4056.19	-3971.55	-3893.18	-3783.73	-3594.63	-3366.22	-3103.85	-2791.77
	15	-4080.19	-3991.86	-3928.35	-3817.48	-3663.29	-3447.57	-3169.22	-2868.25
	20	-4090.99	-4016.31	-3956.18	-3847.83	-3697.39	-3491.5	-3232.06	-2929.42
540	-20	-3868.18	-3737.62	-3618.44	-3457.78	-3212.36	-2989.74	-2720	-2452.56
	-15	-3996.51	-3883.83	-3721.72	-3574.82	-3364.94	-3118.24	-2867.86	-2600.46
	-10	-4120.78	-3994.94	-3842.54	-3686.46	-3483.08	-3247.62	-2982.47	-2726.23
	-5	-4224.48	-4101.87	-3963.4	-3803.87	-3613.9	-3368.3	-3111.93	-2795.24
	5	-4336.33	-4242.8	-4152.56	-4009.8	-3804.77	-3593.24	-3307.49	-2995
	10	-4363.19	-4274.46	-4194.41	-4079.72	-3899.8	-3650.11	-3369.84	-3043.9
	15	-4385.41	-4307.9	-4230.1	-4115.81	-3959.31	-3736.2	-3444.82	-3122.45
	20	-4400.37	-4325.25	-4259.67	-4149.14	-3989.14	-3773.84	-3505	-3181.57
610	-20	-4078.86	-3939.66	-3832.61	-3659.5	-3414.85	-3167.49	-2898.29	-2617.18
	-15	-4213.98	-4096.35	-3927.67	-3786	-3555.29	-3305.57	-3045.9	-2770.73
	-10	-4336	-4210	-4063.23	-3906.29	-3681.84	-3435.51	-3162.91	-2898.16
	-5	-4444.52	-4322.59	-4182.18	-4015.91	-3815.68	-3569.32	-3294.81	-2966.77
	5	-4556.68	-4458.31	-4366.08	-4223.94	-4009.45	-3789.59	-3491.01	-3173.06
	10	-4581.87	-4493.17	-4406.98	-4289.28	-4106.29	-3847.96	-3555.87	-3222.04
	15	-4607.47	-4519.82	-4441.6	-4328.95	-4165.2	-3927.52	-3635.25	-3300.27
	20	-4619.89	-4536.93	-4473.63	-4360.98	-4198.93	-3973.75	-3697.58	-3356.36
680	-20	-4227.51	-4084.41	-3978.15	-3806.37	-3547.12	-3305.81	-3018.96	-2739.16
	-15	-4366.3	-4238.5	-4077.63	-3934.44	-3702.82	-3435.62	-3171.99	-2892.84
	-10	-4491.59	-4361.04	-4214.9	-4055.78	-3823.26	-3573.97	-3301.95	-3019.74
	-5	-4598.15	-4475.25	-4335.29	-4165.85	-3959.04	-3707.15	-3421.32	-3099.88
	5	-4712.91	-4595.9	-4518.95	-4374.38	-4158.84	-3928.42	-3630.12	-3299.07
	10	-4739.51	-4645.77	-4558.49	-4439.45	-4253.39	-3991.39	-3693.38	-3359.87
	15	-4760.52	-4673.79	-4603.99	-4476.77	-4311.68	-4076.46	-3772.69	-3438.13
	20	-4777.92	-4690.43	-4627.62	-4513.04	-4345.07	-4114.62	-3828.56	-3487.53

Appendix F: Wheat integrated biomethanol (WIBM) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -5003.87 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	**Precipitation (%)**	**Temperature (^oC)**				
		0.5	**1.5**	**2.5**	**3.5**	**4.5**
400	**-20**	-5346.20	-5553.02	-6165.84	-6772.12	-7187.89
	-10	-5344.16	-5548.00	-6188.50	-6772.68	-7150.98
	10	-5110.64	-5399.99	-6068.29	-6705.28	-7098.77
	20	-5000.35	-5261.99	-5954.41	-6622.19	-7034.23
540	**-20**	-5584.63	-5788.02	-6549.43	-7293.71	-7720.39
	-10	-5539.22	-5788.33	-6560.98	-7316.65	-7737.52
	10	-5299.72	-5582.67	-6432.23	-7203.81	-7632.76
	20	-5122.71	-5486.46	-6344.38	-7125.82	-7571.83
680	**-20**	-5794.19	-5997.89	-6833.91	-7682.90	-8041.13
	-10	-5704.24	-5969.28	-6837.97	-7678.32	-8024.30
	10	-5490.88	-5796.19	-6722.14	-7589.17	-7931.85
	20	-5282.35	-5674.13	-6626.81	-7502.14	-7834.79

Appendix G: Corn integrate bioelectricity (CIBE) model output

Life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -10996.7 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
400	**-20**	-10107.6	-9867.98	-9560.49	-9124.71	-8739.24	-8193.83	-7756.31	-7326.57
	-15	-10184.5	-9952.42	-9682.71	-9276.51	-8886.91	-8347.83	-7868.45	-7463.14
	-10	-10235.9	-10021.6	-9776.8	-9411.95	-9046.11	-8462.42	-7993.07	-7552.21
	-5	-10259.5	-10087.1	-9817.2	-9481.93	-9154.02	-8625.31	-8098.3	-7640.88
	5	-10342.1	-10158	-9899.74	-9572.24	-9250.29	-8763.81	-8270.58	-7793.3
	10	-10374.7	-10193.4	-9938.02	-9611	-9298.02	-8812	-8326.83	-7860.7
	15	-10384	-10215.5	-9985.29	-9646.51	-9344.15	-8858.72	-8358.83	-7912.55
	20	-10389.4	-10227.5	-10010.7	-9692.72	-9383.35	-8901.65	-8408.37	-7949.44
470	**-20**	-10264.3	-10051.5	-9772.01	-9346.89	-8967.76	-8463.29	-7979.74	-7549.02
	-15	-10328.2	-10131.2	-9857.64	-9532.34	-9133.83	-8572.35	-8095.15	-7669.46
	-10	-10363.9	-10184.8	-9925.91	-9620.45	-9292.24	-8728.9	-8215.65	-7762.58
	-5	-10398.9	-10226	-9993.02	-9666.53	-9373.41	-8877.99	-8341.83	-7871.45
	5	-10456.3	-10307.3	-10062.3	-9755.5	-9453.01	-8964.7	-8495.08	-8009.01
	10	-10470.7	-10339.8	-10104.4	-9792.43	-9488.22	-9021.6	-8531.86	-8078.36
	15	-10475.2	-10355	-10128.4	-9830.92	-9527.31	-9052.49	-8575.16	-8121.23
	20	-10480.5	-10359.7	-10140.8	-9860.47	-9562.44	-9100.61	-8616.32	-8184.19
540	**-20**	-10421.9	-10219.4	-9955.93	-9610.1	-9229.76	-8685.79	-8211.34	-7779.37
	-15	-10457.1	-10276	-10026.3	-9728.6	-9377.24	-8824.97	-8349.98	-7893.07
	-10	-10483.3	-10329	-10099.7	-9797.52	-9490.7	-8991.22	-8474.19	-7998.91
	-5	-10522.4	-10358.9	-10133.4	-9856.7	-9545.8	-9071.34	-8604.64	-8096.39
	5	-10573.7	-10424.5	-10211.2	-9931.17	-9626.03	-9163.94	-8700.59	-8226.62
	10	-10585.5	-10441	-10237.7	-9967.79	-9666.23	-9192.28	-8755.54	-8278.18
	15	-10591.2	-10445.7	-10261.8	-9991.25	-9700.54	-9234.87	-8782.95	-8328.48
	20	-10590	-10462.1	-10255.5	-10012.9	-9737.67	-9271.13	-8832.77	-8375.83
610	**-20**	-10580.2	-10387	-10163.2	-9877.51	-9529.06	-8957.61	-8482.59	-8034.99
	-15	-10601.5	-10437.7	-10213.7	-9942.2	-9660.85	-9111.29	-8618.56	-8146.69
	-10	-10632.1	-10472.3	-10259.6	-9990.12	-9725.81	-9234.55	-8748.9	-8274.15
	-5	-10664.8	-10526	-10290.9	-10045.8	-9772.75	-9284.81	-8837.56	-8380.67
	5	-10698.5	-10571.9	-10361.6	-10105.4	-9838.38	-9370.78	-8938.56	-8493.46
	10	-10700.3	-10578.7	-10381.2	-10136.5	-9869.28	-9402.36	-8976.7	-8547.45
	15	-10708.9	-10586.4	-10396.3	-10149.8	-9903.86	-9442.52	-9014.28	-8584.68
	20	-10711.5	-10597.2	-10402.5	-10158.5	-9926.93	-9479.67	-9054.09	-8629.26
680	**-20**	-10701.5	-10562.7	-10333.5	-10064.1	-9805.06	-9221.38	-8753.25	-8286.62
	-15	-10717.1	-10599.1	-10384.2	-10116.8	-9859	-9363.69	-8887.87	-8413.51
	-10	-10752.4	-10642.1	-10423.1	-10170.1	-9911.72	-9436.37	-9018.96	-8535.32
	-5	-10762.7	-10674.5	-10470.8	-10195.1	-9959.34	-9473.62	-9058.25	-8624.23
	5	-10789.9	-10698.2	-10510	-10262.4	-10027.6	-9559.47	-9157.48	-8732.09
	10	-10795.6	-10715.1	-10515.3	-10287.7	-10059.6	-9594.96	-9179.79	-8777.44
	15	-10800.8	-10717.4	-10530.5	-10295.5	-10085	-9644.15	-9218.69	-8808.2
	20	-10819.4	-10736.7	-10540.2	-10299.7	-10093.1	-9673.13	-9257.9	-8850.88

Appendix H: Soybean integrated bioelectricity (SIBE) model output

Life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -1350.04 kg CO_2-equiv. ha^{-1}].

CO_2 (ppm)	Precipitation (%)	Temperature (°C)							
		1.5	2	2.5	3	3.5	4	4.5	5
400	-20	-1085.34	-999.777	-890.104	-797.651	-644.776	-521.346	-382.315	-234.652
	-15	-1169.73	-1082.69	-967.567	-863.77	-729.788	-583.217	-442.639	-278.564
	-10	-1228.85	-1138.03	-1030.79	-932.124	-789.711	-650.139	-484.283	-327.939
	-5	-1293.24	-1206.36	-1099.9	-987.24	-850.001	-705.545	-553.204	-365.011
	5	-1370.5	-1285.83	-1205.28	-1107.55	-964.262	-818.462	-643.453	-438.695
	10	-1389.22	-1315.95	-1241.11	-1139.28	-1008.21	-853.357	-675.021	-465.786
	15	-1400.98	-1332.29	-1259.92	-1166.83	-1048.14	-892.378	-713.467	-499.424
	20	-1411.23	-1345.45	-1282.82	-1181.64	-1062.38	-914.322	-733.777	-527.074
470	-20	-1287.01	-1198.11	-1095.98	-978.731	-817.746	-677.412	-526.458	-361.686
	-15	-1374.93	-1283.88	-1164.92	-1057.35	-899.681	-749.553	-595.56	-422.466
	-10	-1439.54	-1342.47	-1235.49	-1118.71	-977.846	-819.94	-648.905	-465.152
	-5	-1512.61	-1416.45	-1308.59	-1184.81	-1049.55	-886.155	-712.078	-509.086
	5	-1585.3	-1503.7	-1420.42	-1308.44	-1156.63	-1001.09	-809.301	-590.507
	10	-1601.46	-1526.42	-1450.67	-1349.84	-1203.41	-1034.55	-845.951	-614.576
	15	-1618.17	-1539.4	-1473.11	-1370.16	-1230.27	-1075.07	-876.573	-650.518
	20	-1625.49	-1555.69	-1489.59	-1389.54	-1262.13	-1098.94	-905.404	-678.525
540	-20	-1436.2	-1335.14	-1238.11	-1118.95	-940.568	-796.164	-628.575	-453.385
	-15	-1521.63	-1432.92	-1302.01	-1183.76	-1031.79	-866.174	-700.908	-522.039
	-10	-1602.68	-1502.76	-1376.72	-1255.46	-1105.15	-940.884	-762.88	-576.43
	-5	-1669.84	-1569.99	-1454.06	-1327.56	-1183.84	-1010.14	-832.101	-612.602
	5	-1740.94	-1658.47	-1572.05	-1456.01	-1296.77	-1136.96	-933.206	-701.902
	10	-1755.99	-1678.05	-1600.36	-1495.43	-1351.46	-1168.19	-965.379	-721.179
	15	-1772.18	-1700.37	-1623.55	-1516.67	-1386.06	-1213.94	-1002.48	-759.335
	20	-1780.24	-1710.87	-1641.26	-1539.29	-1403.59	-1233.33	-1031.62	-785.887
610	-20	-1541.04	-1434.94	-1346.17	-1215.19	-1038.83	-875.342	-705.926	-520.999
	-15	-1630.93	-1538.7	-1402.73	-1290.81	-1120.67	-952.178	-778.442	-592.574
	-10	-1712.23	-1609.98	-1492.2	-1364.22	-1200.03	-1027.28	-842.5	-648.139
	-5	-1781.34	-1684.57	-1563.55	-1434.11	-1280.5	-1104.77	-914.565	-685.14
	5	-1851.56	-1767.49	-1677.8	-1561.1	-1396.6	-1229.75	-1016.12	-777.976
	10	-1866.89	-1787.49	-1706.55	-1598.73	-1452.58	-1262.05	-1050.08	-799.528
	15	-1885.49	-1806.46	-1728.6	-1621.79	-1485.27	-1304.26	-1090.31	-834.132
	20	-1892.11	-1816.79	-1747.69	-1644.21	-1504.84	-1328.29	-1120.62	-860.369
680	-20	-1617.26	-1505.79	-1417.58	-1286.44	-1099.33	-941.255	-758.898	-571.946
	-15	-1707.91	-1607.7	-1476.93	-1364.29	-1192.03	-1011.46	-835.275	-643.983
	-10	-1791.92	-1686.42	-1566.87	-1438.08	-1267.77	-1091.44	-906.699	-701.024
	-5	-1859.62	-1761.42	-1641.09	-1507.55	-1348.88	-1169.59	-971.326	-742.166
	5	-1931.69	-1836.57	-1754.06	-1634.52	-1469.64	-1295.65	-1080.37	-832.534
	10	-1946.92	-1863.94	-1782.21	-1673.44	-1524	-1330.49	-1113.57	-859.91
	15	-1963.73	-1883.51	-1811.63	-1694.83	-1556.24	-1376.62	-1152.63	-897.491
	20	-1973.53	-1893.5	-1825.5	-1720.27	-1575.94	-1395.64	-1180.57	-918.971

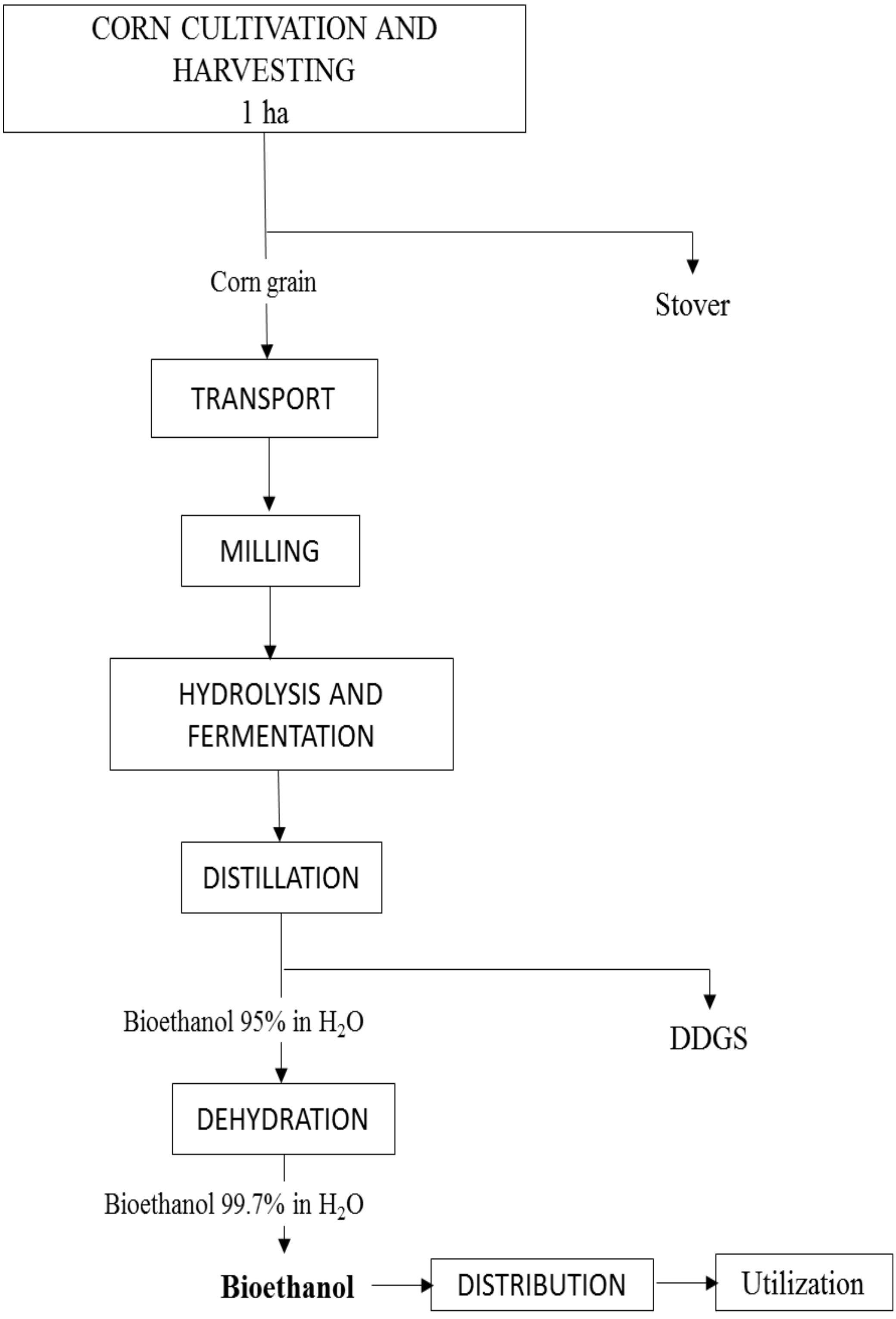
Appendix I: Wheat integrated bioelectricity (WIBE) model output

CML2001, GWP100 years, life cycle GHG emissions savings (kg CO_2-equiv. ha^{-1}) [Baseline scenario = -4648.93 kg CO_2-equiv. ha^{-1}]

CO_2 (ppm)	Precipitation (%)	Temperature (^oC)				
		0.5	1.5	2.5	3.5	4.5
400	-20	-5133.23	-5447.18	-5901.49	-6328.25	-6476.51
	-10	-5102.97	-5413.81	-5887.32	-6299.90	-6431.99
	10	-4838.74	-5220.33	-5705.06	-6171.59	-6331.67
	20	-4695.44	-5068.76	-5573.10	-6068.16	-6249.92
540	-20	-5410.14	-5691.68	-6175.74	-6693.47	-6863.89
	-10	-5342.99	-5654.16	-6147.68	-6677.55	-6851.50
	10	-5058.35	-5422.15	-5971.48	-6524.95	-6717.06
	20	-4868.06	-5295.86	-5858.04	-6425.93	-6638.16
680	-20	-5657.43	-5897.90	-6380.59	-6954.72	-7081.61
	-10	-5553.34	-5841.70	-6352.14	-6925.81	-7049.38
	10	-5286.63	-5623.83	-6185.78	-6791.90	-6932.15
	20	-5072.20	-5477.84	-6071.95	-6691.22	-6832.42

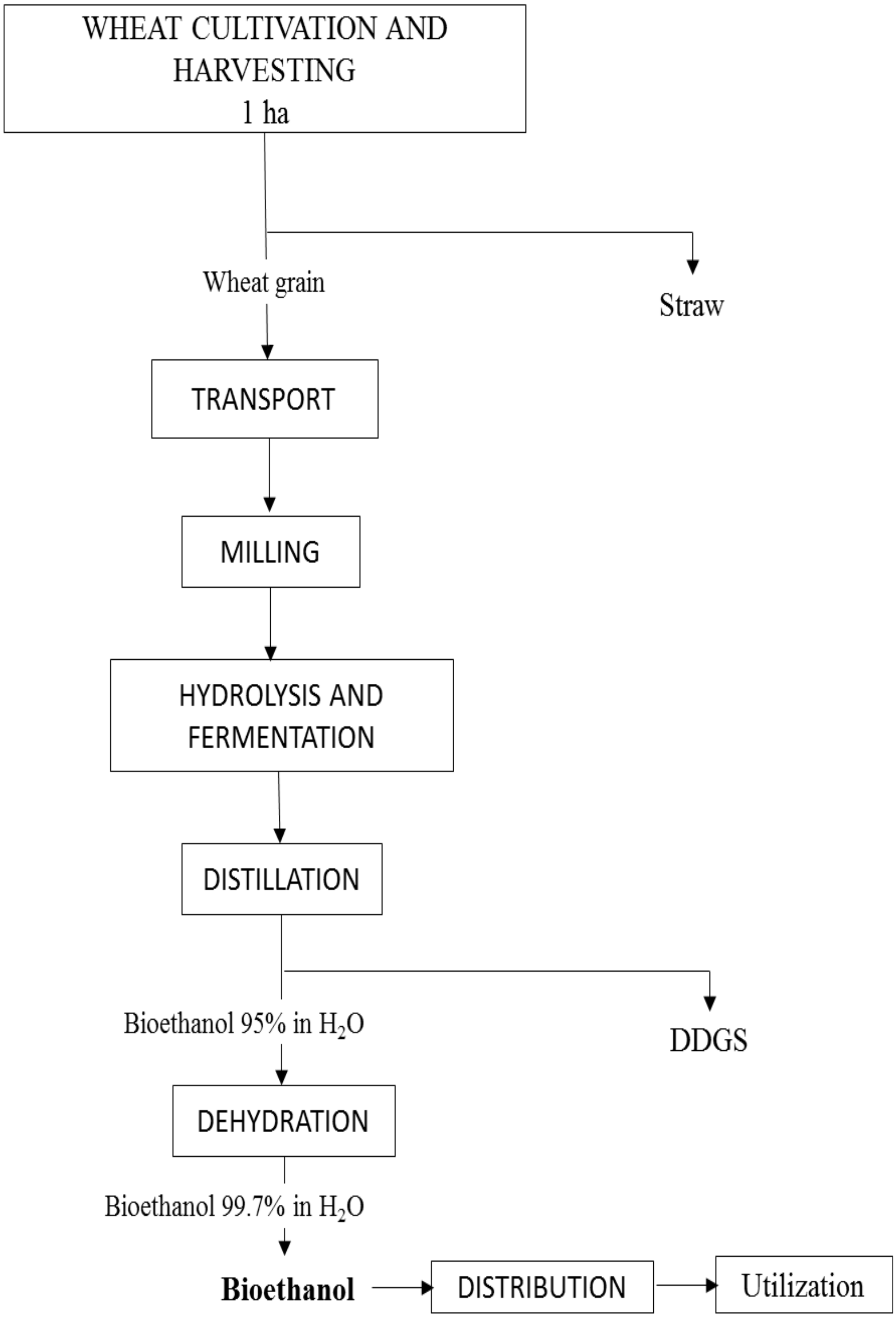
Appendix J: Corn bioethanol (CBE) model

Flow Chart for the Production of Bioethanol from Corn Grain



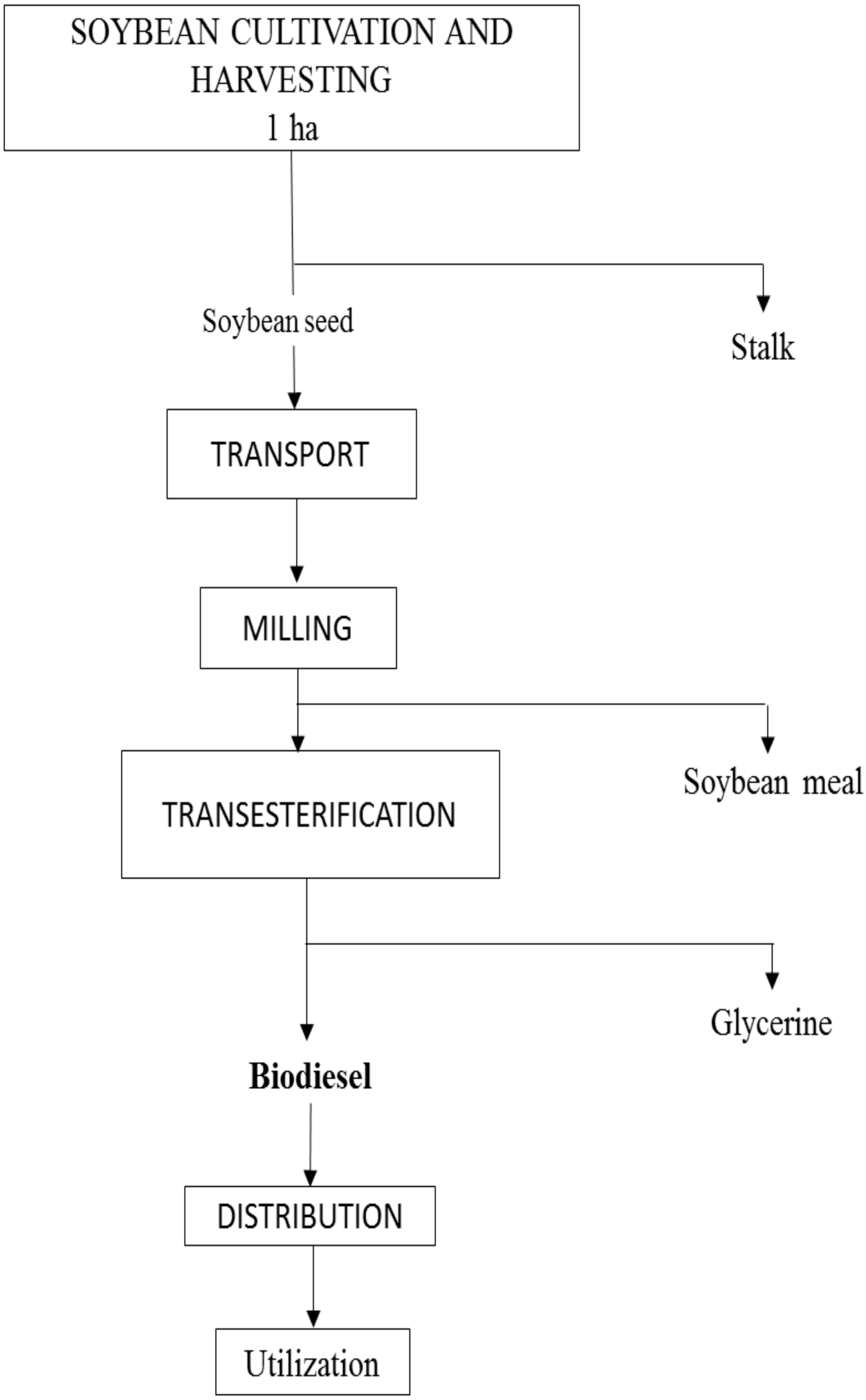
Appendix K: Wheat bioethanol (WBE) model

Flow Chart for the Production of Bioethanol from Wheat Grain



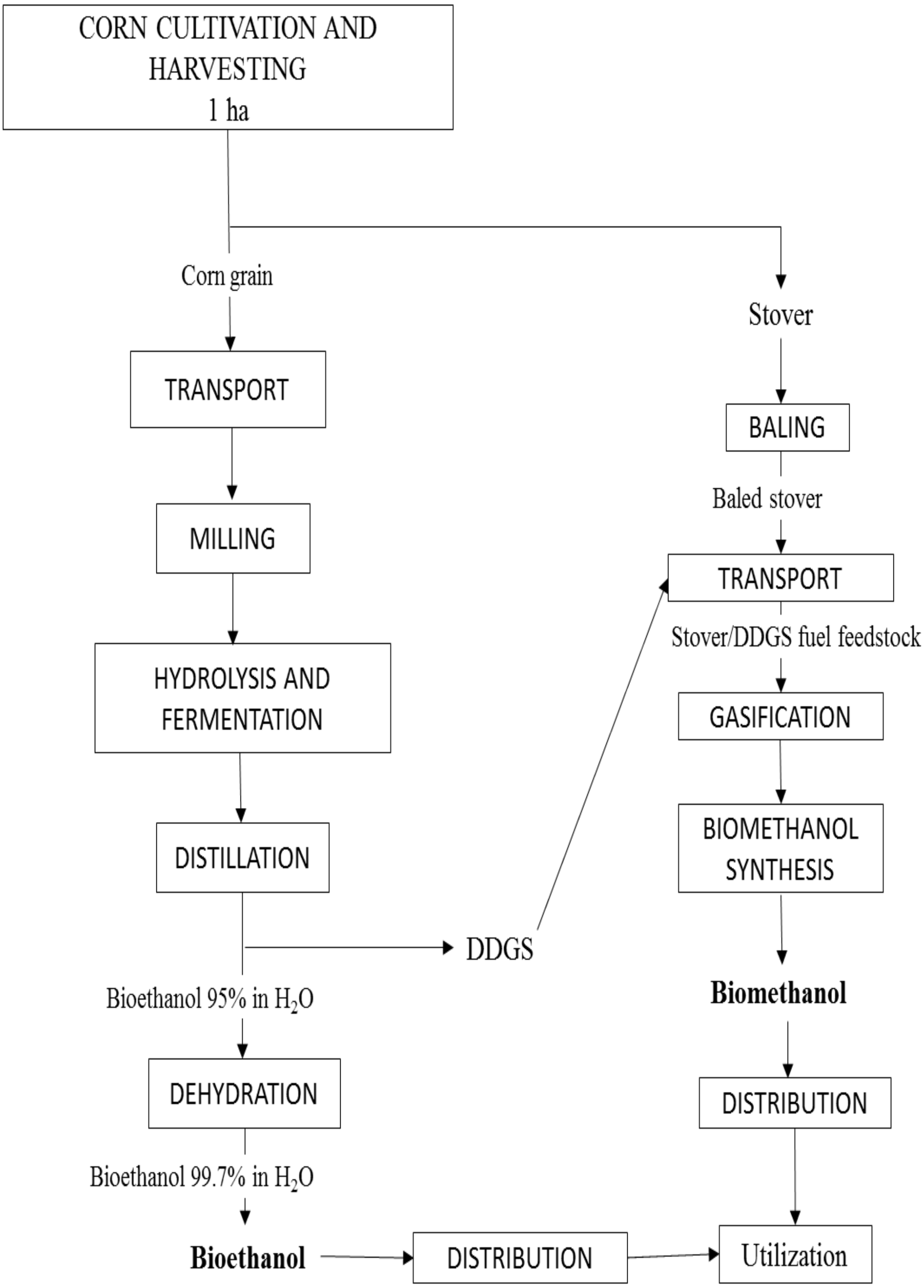
Appendix L: Soybean biodiesel (SBD) model

Flow Chart for the Production of Biodiesel from Soybean Seed



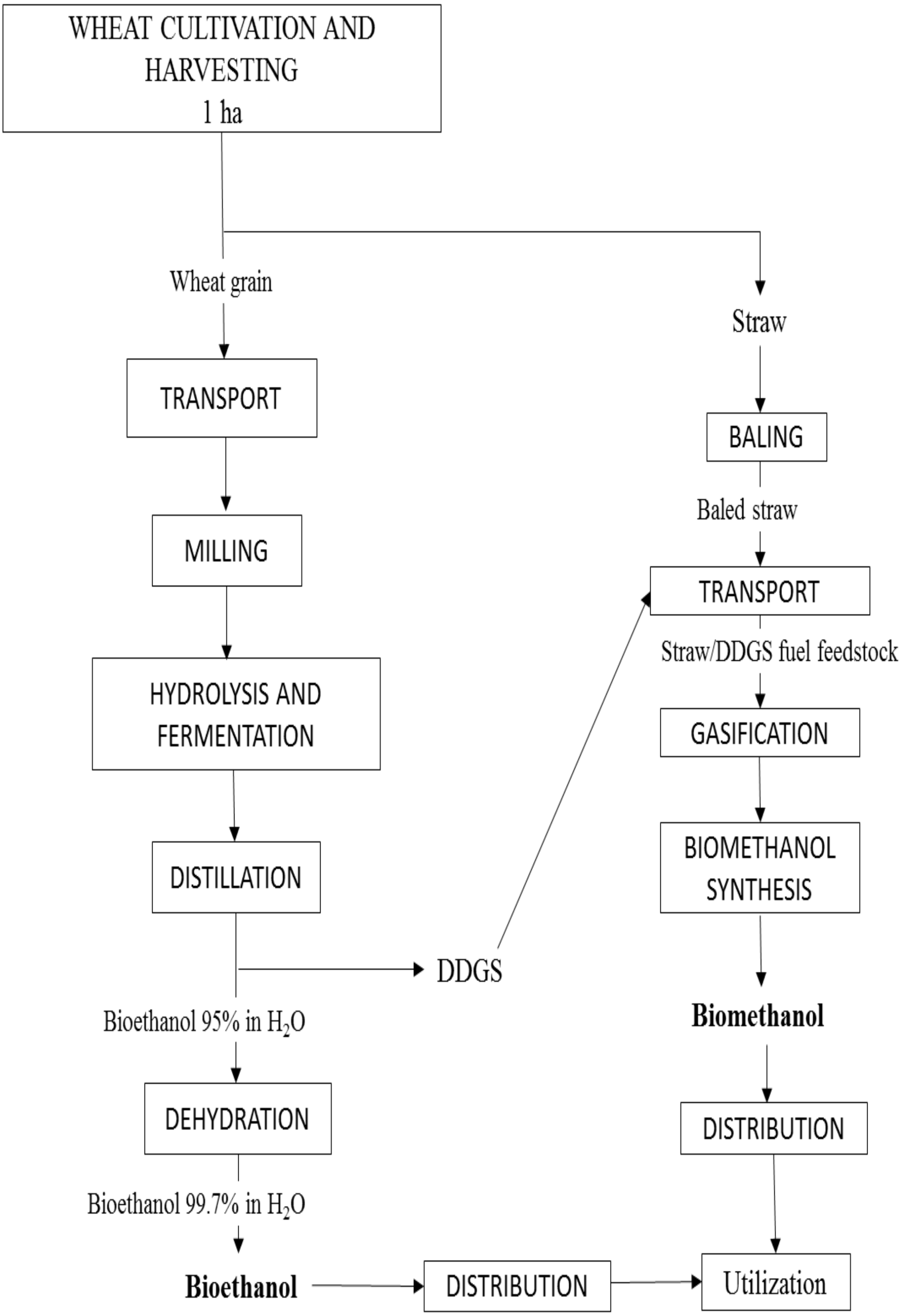
Appendix M: Corn integrated biomethanol (CIBM) model

Flow Chart for the Integrated Production of Bioethanol from Corn Grain Using Stover and DDGS as Fuel Sources for Biomethanol Synthesis



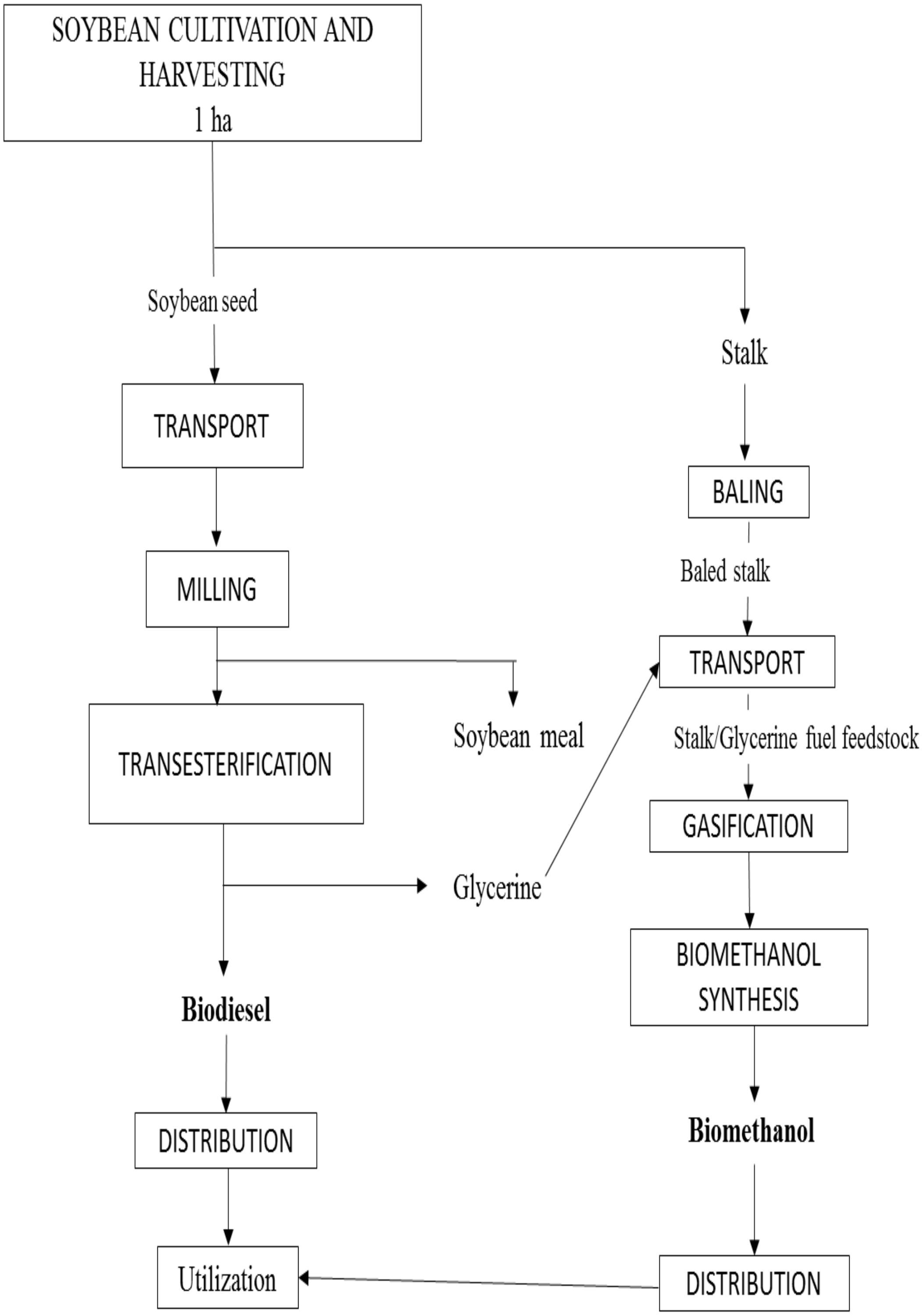
Appendix N: Wheat integrated biomethanol (WIBM) model

Flow Chart for the Integrated Production of Bioethanol from Wheat Grain Using Straw and DDGS as Fuel Sources for Biomethanol Synthesis



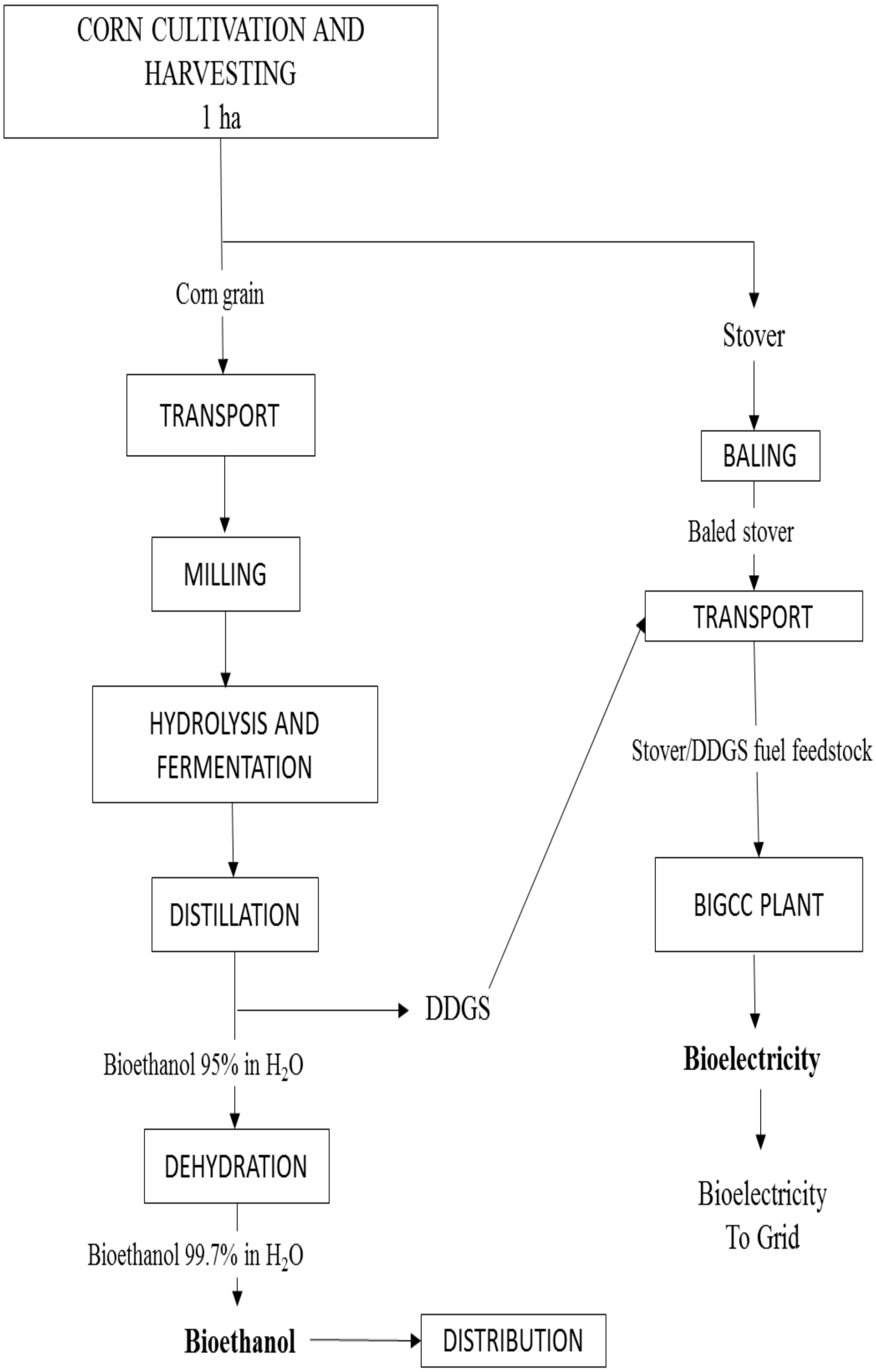
Appendix O: Soybean integrated biomethanol (SIBM) model

Flow Chart for the Integrated Production of Biodiesel from Soybean Seed Using Stalk and Glycerine as Fuel Sources for Biomethanol Synthesis



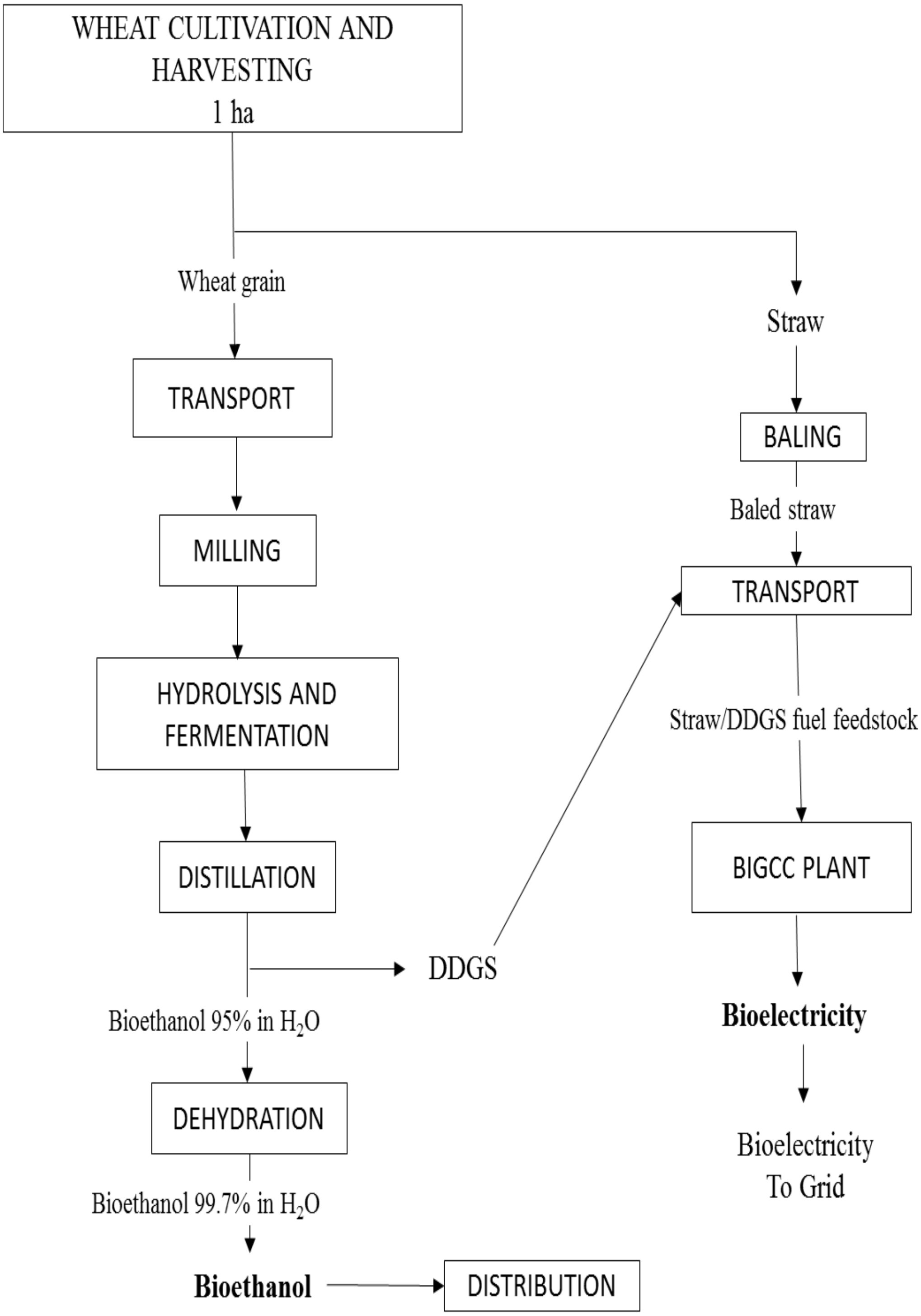
Appendix P: Corn integrated bioelectricity (CIBE) model

Flow Chart for the Integrated Production of Bioethanol from Corn Grain Using Stover and DDGS as Fuel Sources for Bioelectricity Production



Appendix Q: Wheat integrated bioelectricity (WIBE) model

Flow Chart for the Integrated Production of Bioethanol from Wheat Grain Using Straw and DDGS as Fuel Sources for Bioelectricity Production



Appendix R: Soybean integrated bioelectricity (SIBE) model

Flow Chart for the Integrated Production of Biodiesel from Soybean Seed Using Stalk and Glycerine as Fuel Sources for Bioelectricity Production